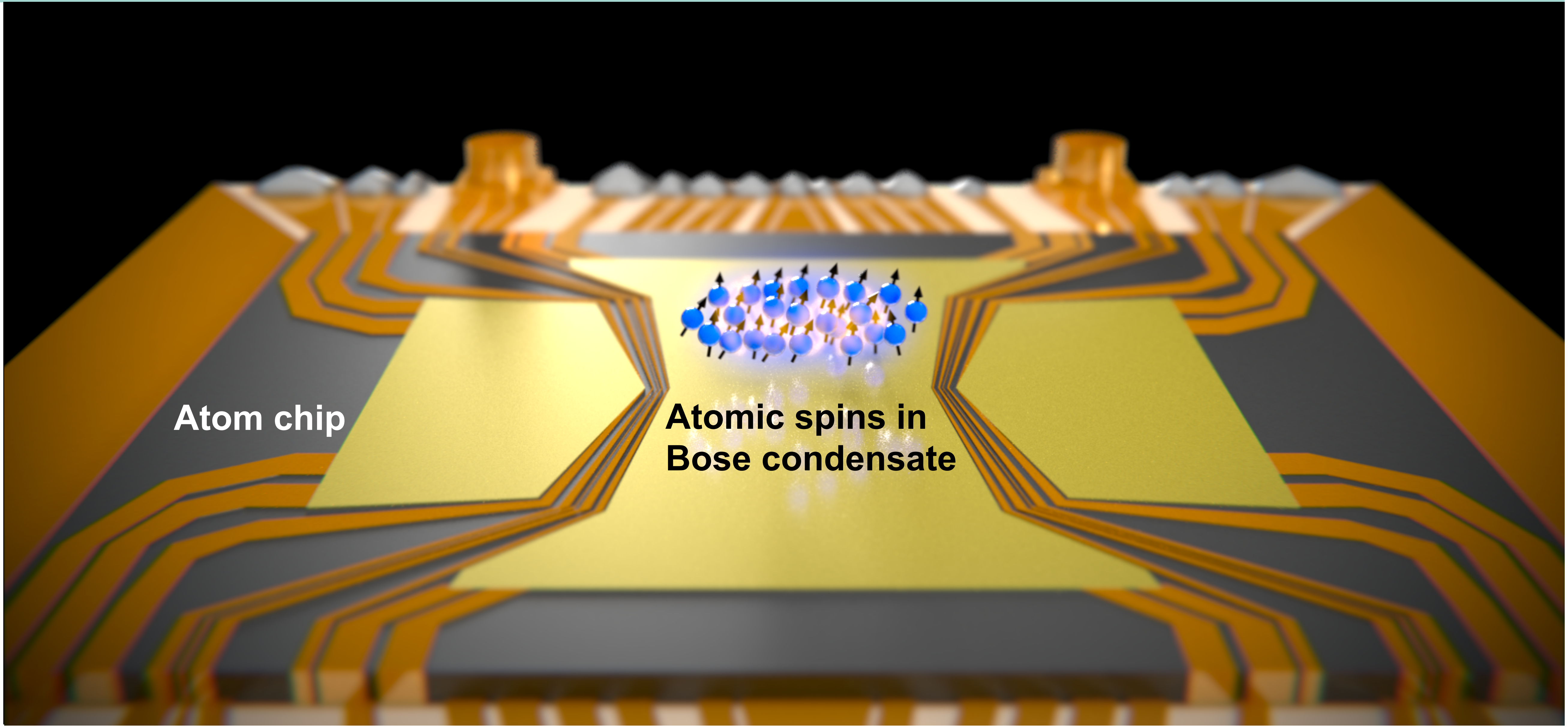
Quantum metrology with entangled atoms

Philipp Treutlein

atom.physik.unibas.ch



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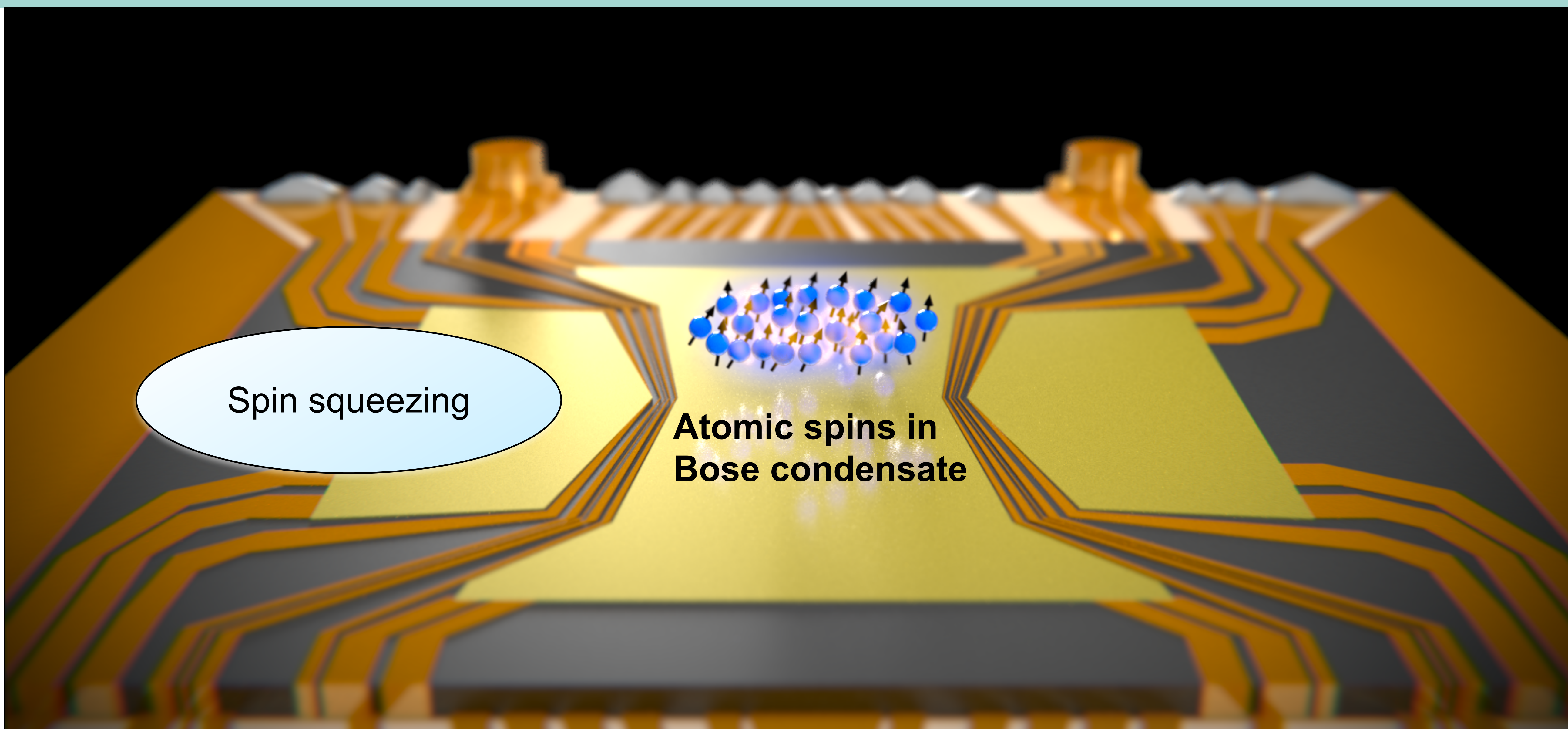

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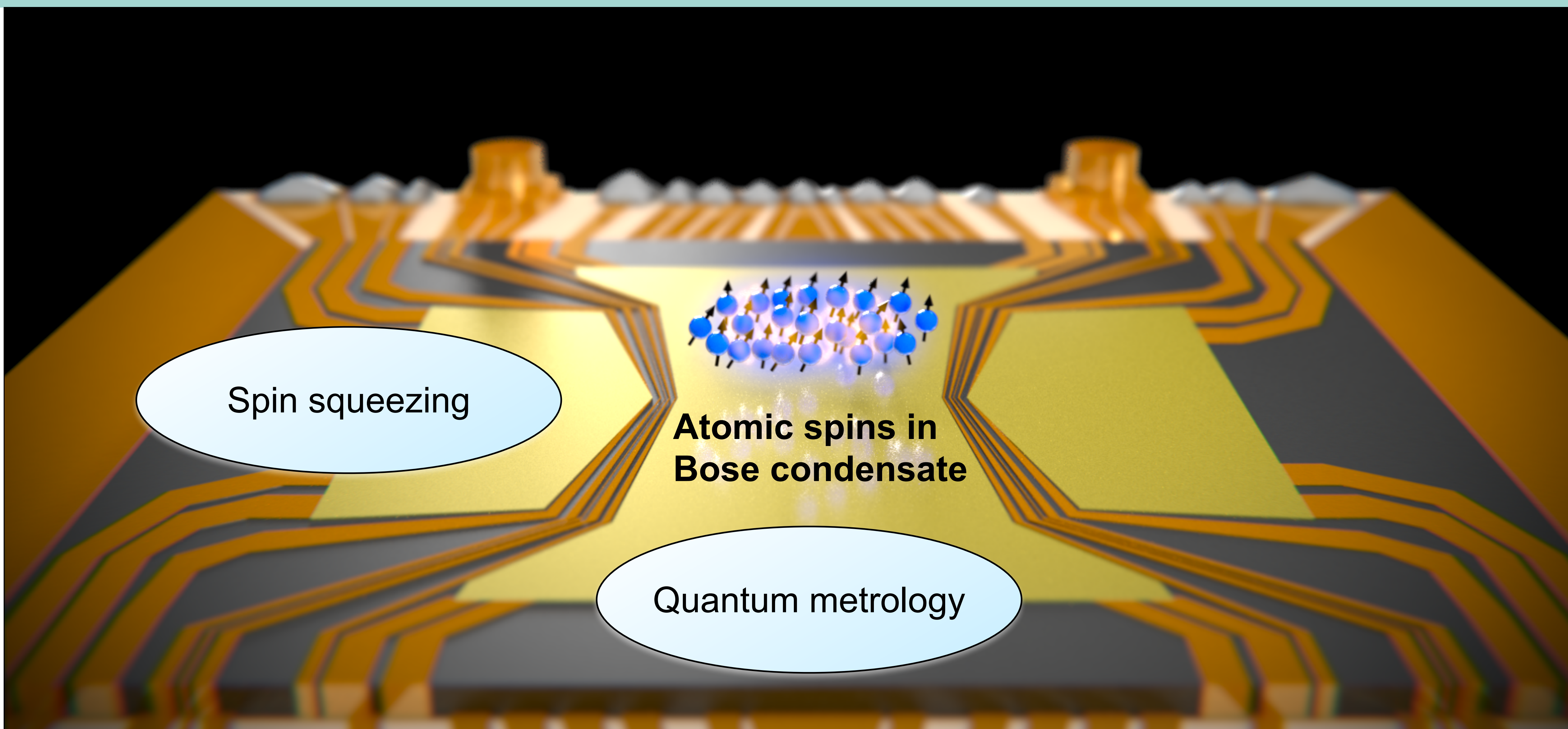

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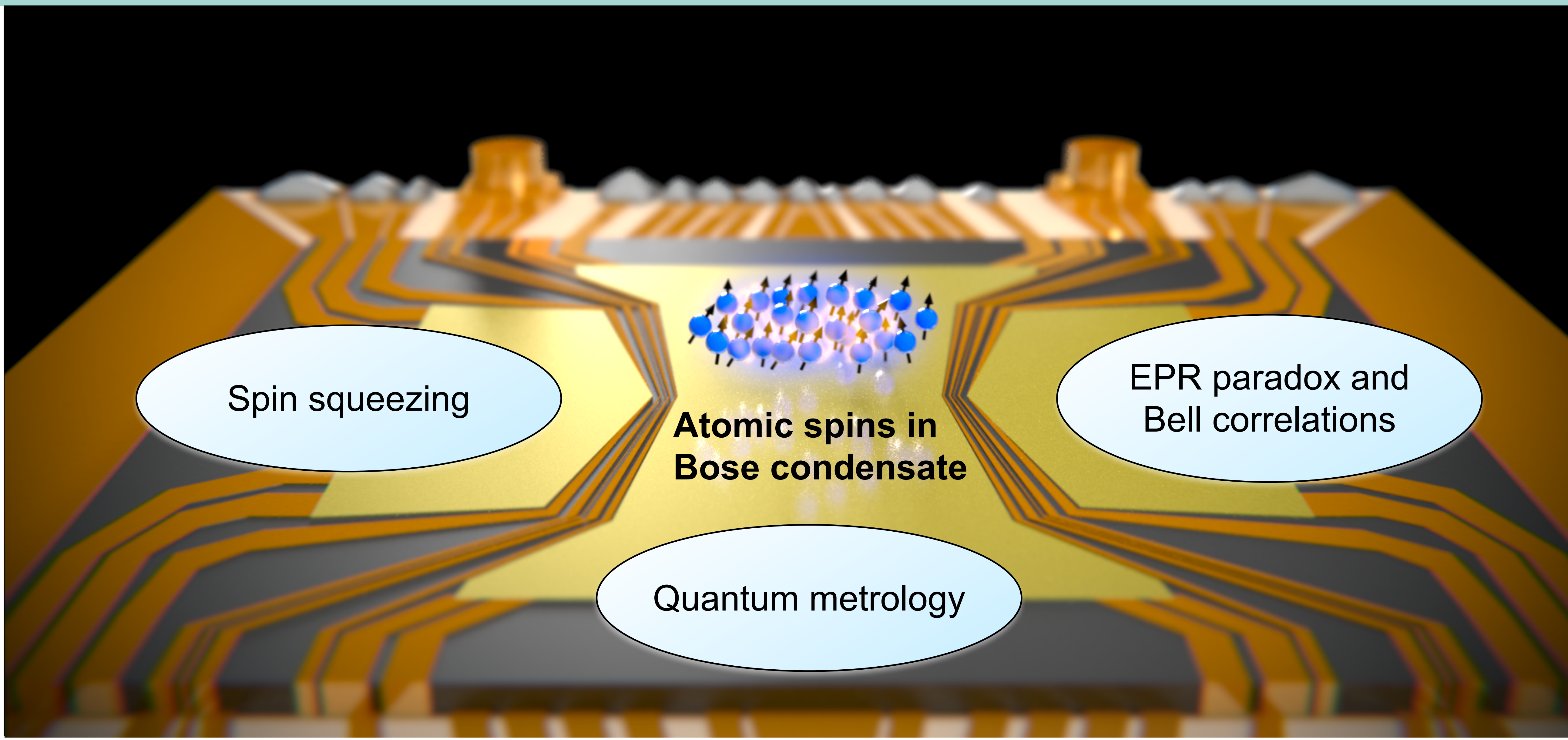


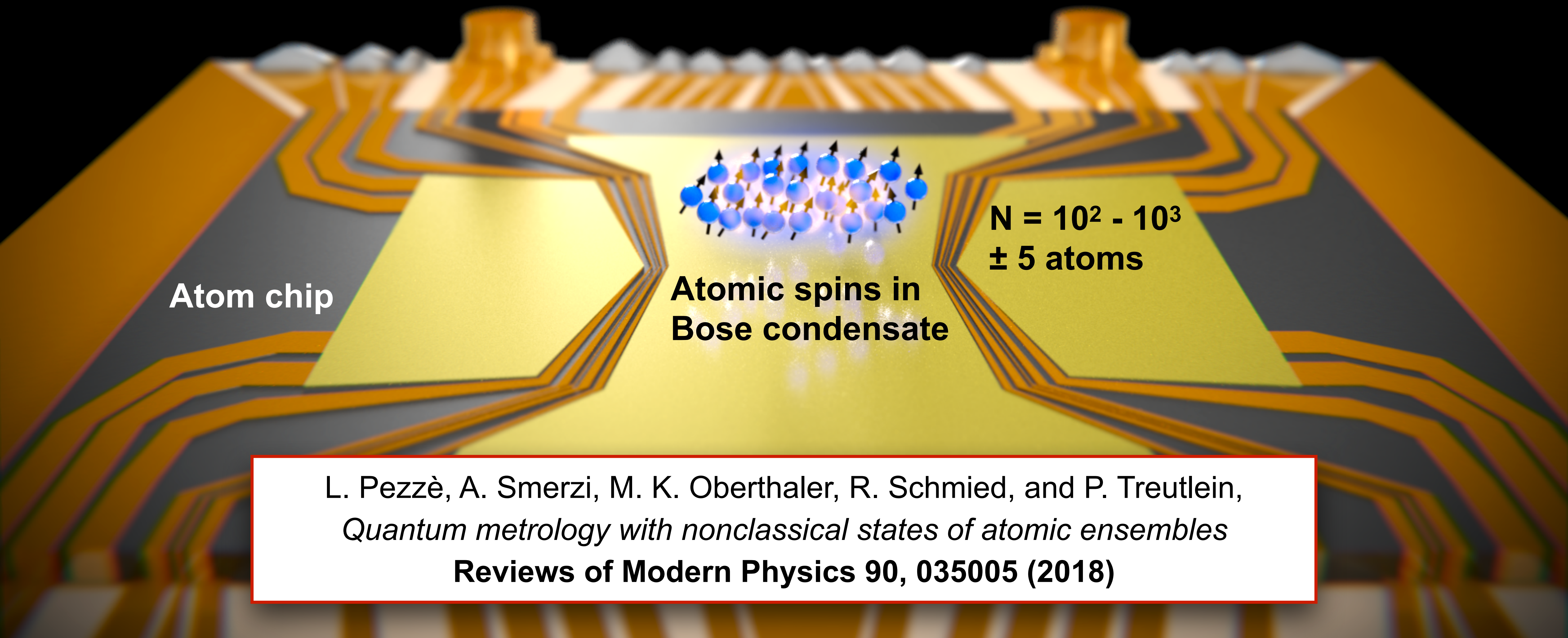
Many-particle entanglement and quantum metrology

Fundamental questions

- different classes of non-classical states
- depth of correlations?
- indistinguishable particles
- detection of correlations?
- usefulness? robustness?

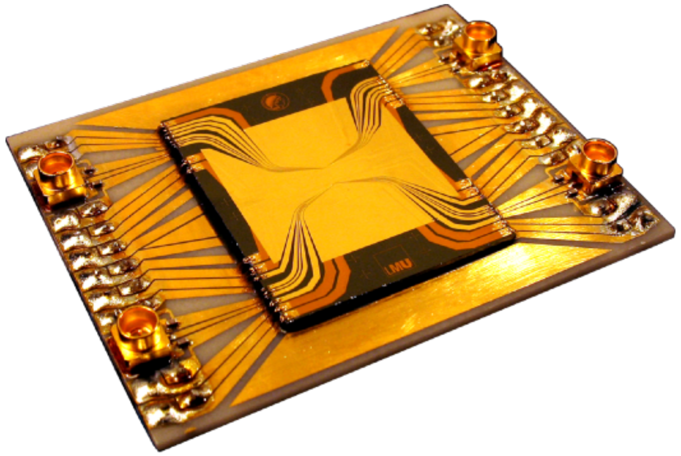
Quantum metrology

- interferometry beyond standard quantum limit (SQL)
- field&force sensing on micrometer scale
- field imaging



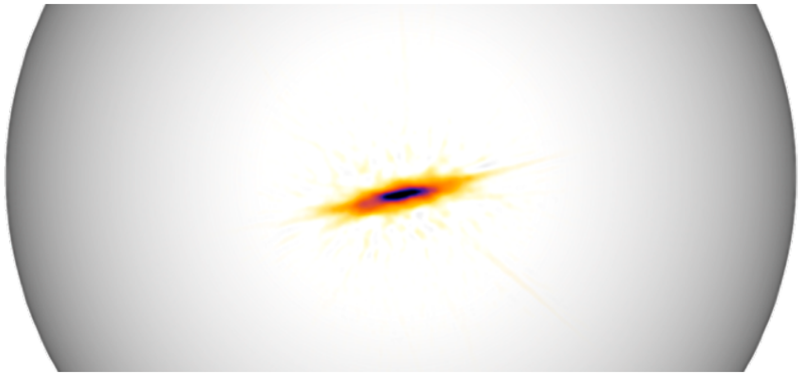
L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein,
Quantum metrology with nonclassical states of atomic ensembles
Reviews of Modern Physics 90, 035005 (2018)

Outline



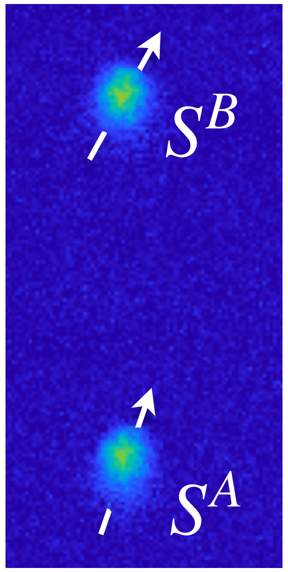
Ultracold atoms on atom chips

Treutlein et al, Phys Rev Lett 92, 203005 (2004)
Böhi et al, Nature Physics 5, 592 (2009)



Spin-squeezed states for quantum metrology

Riedel et al, Nature 464, 1170 (2010)
Ockeloen et al, PRL 111, 143001 (2013)



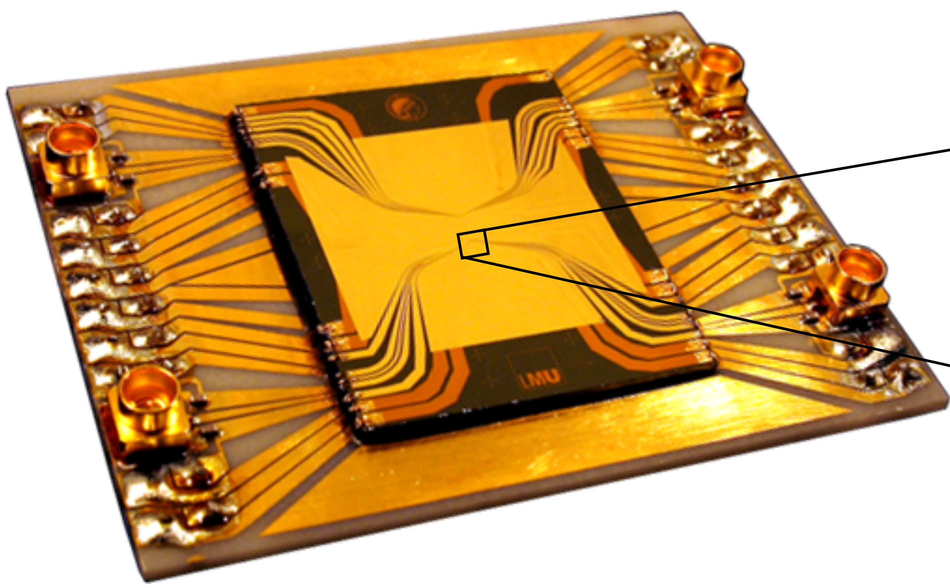
Entanglement, EPR and Bell correlations

Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)

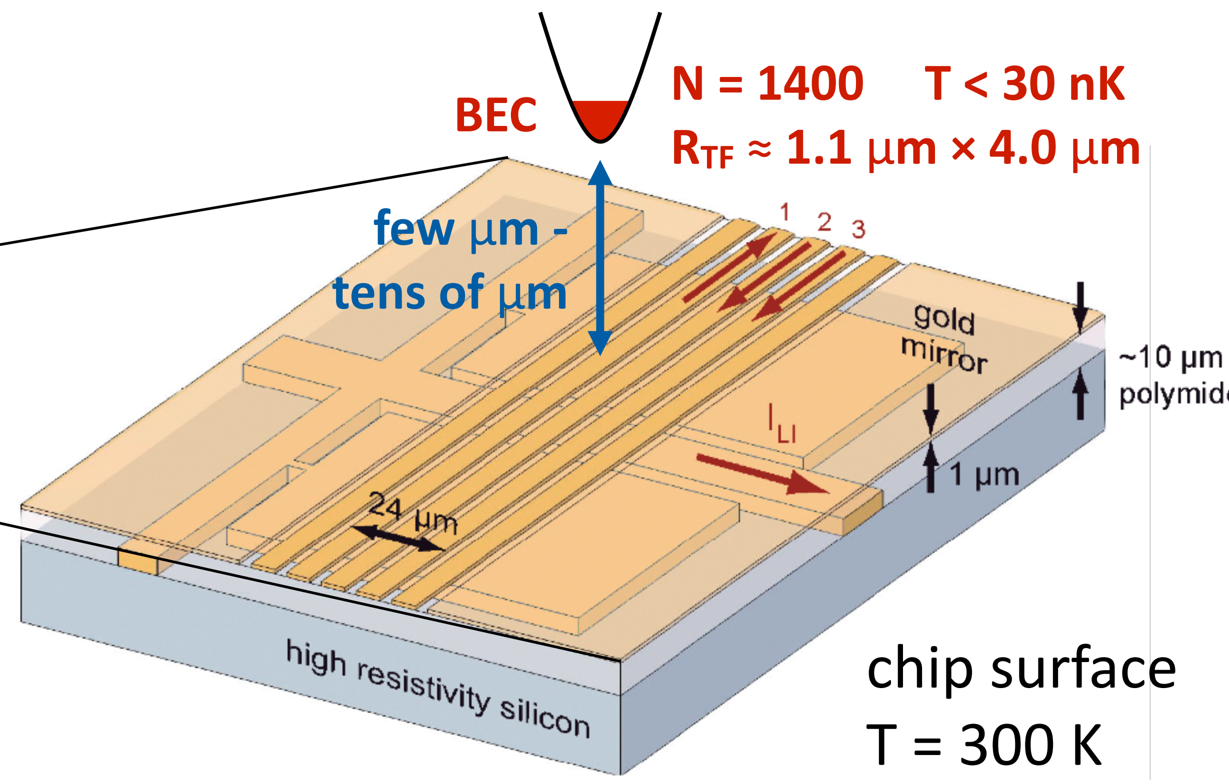
Perspectives for searches of new physics

Atom chips

Microfabricated wire pattern on a chip



Chip-based magnetic microtraps



Ultracold Rubidium atoms at micrometer distance from a room-temperature chip surface

P. Treutlein et al., Coherence in Microchip Traps, Phys. Rev. Lett. 92, 203005 (2004).

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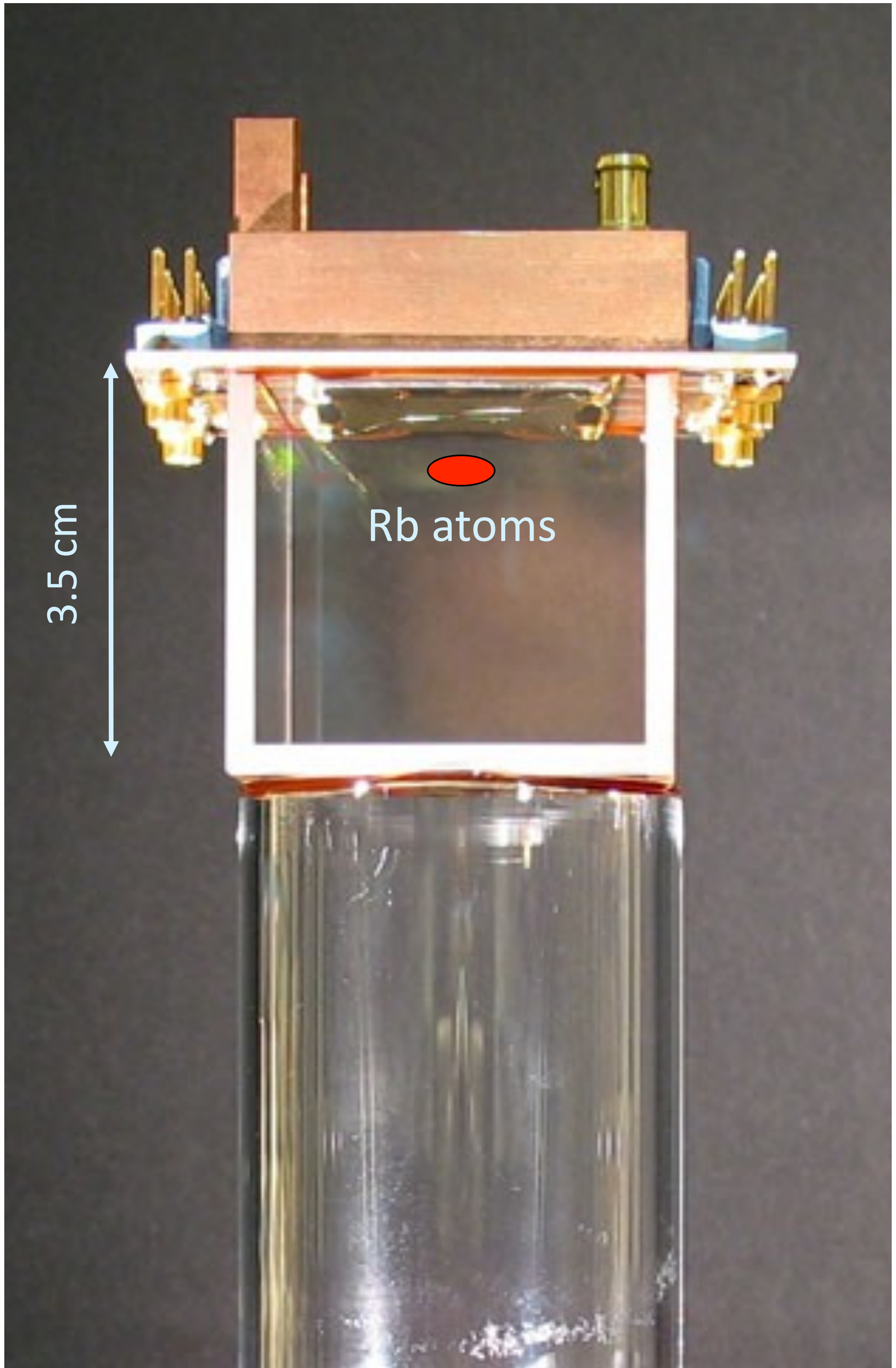
Laser cooling

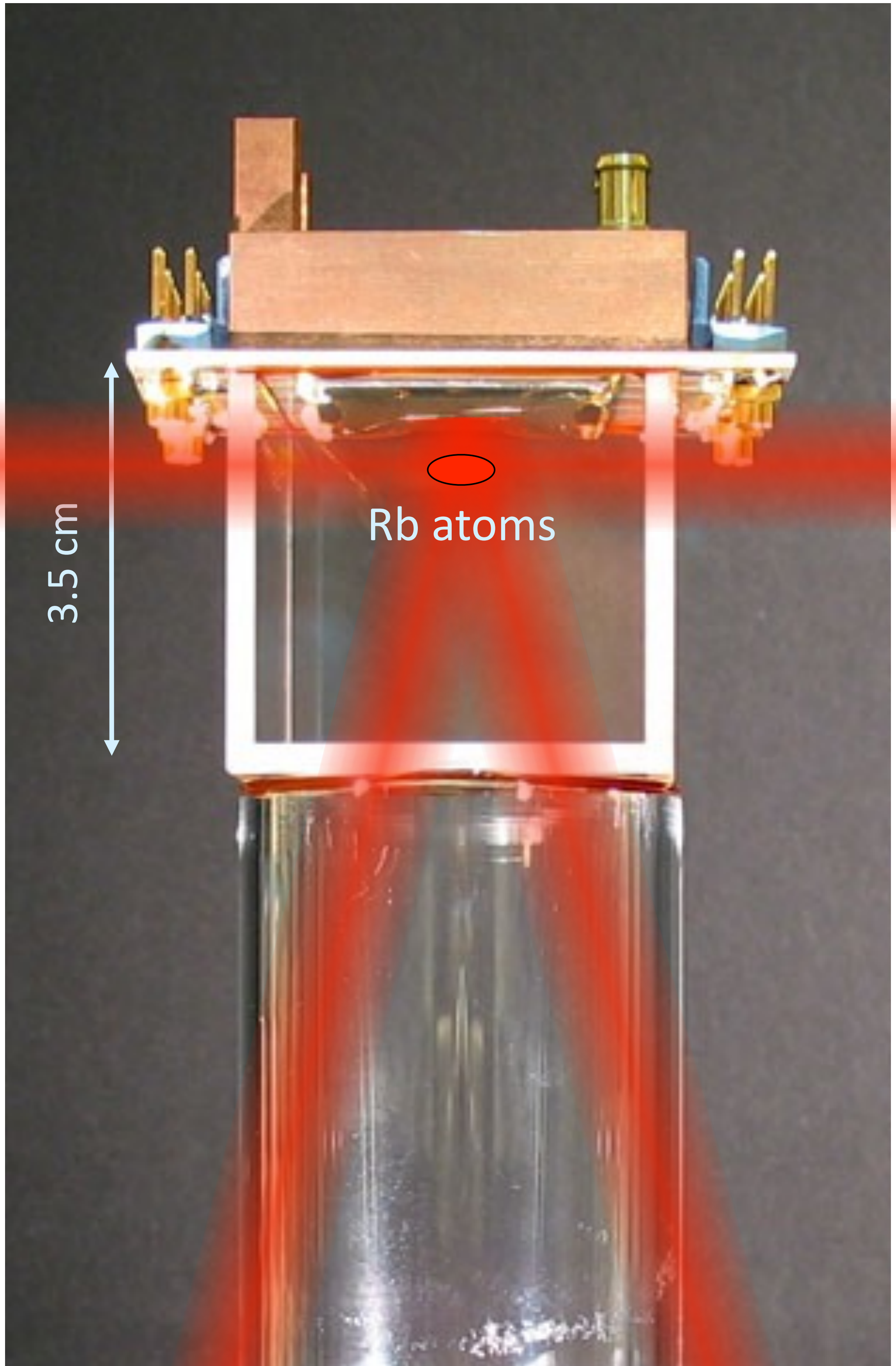
ultra-high vacuum
3×10^{-10} mbar



Laser cooling

ultra-high vacuum
3×10^{-10} mbar

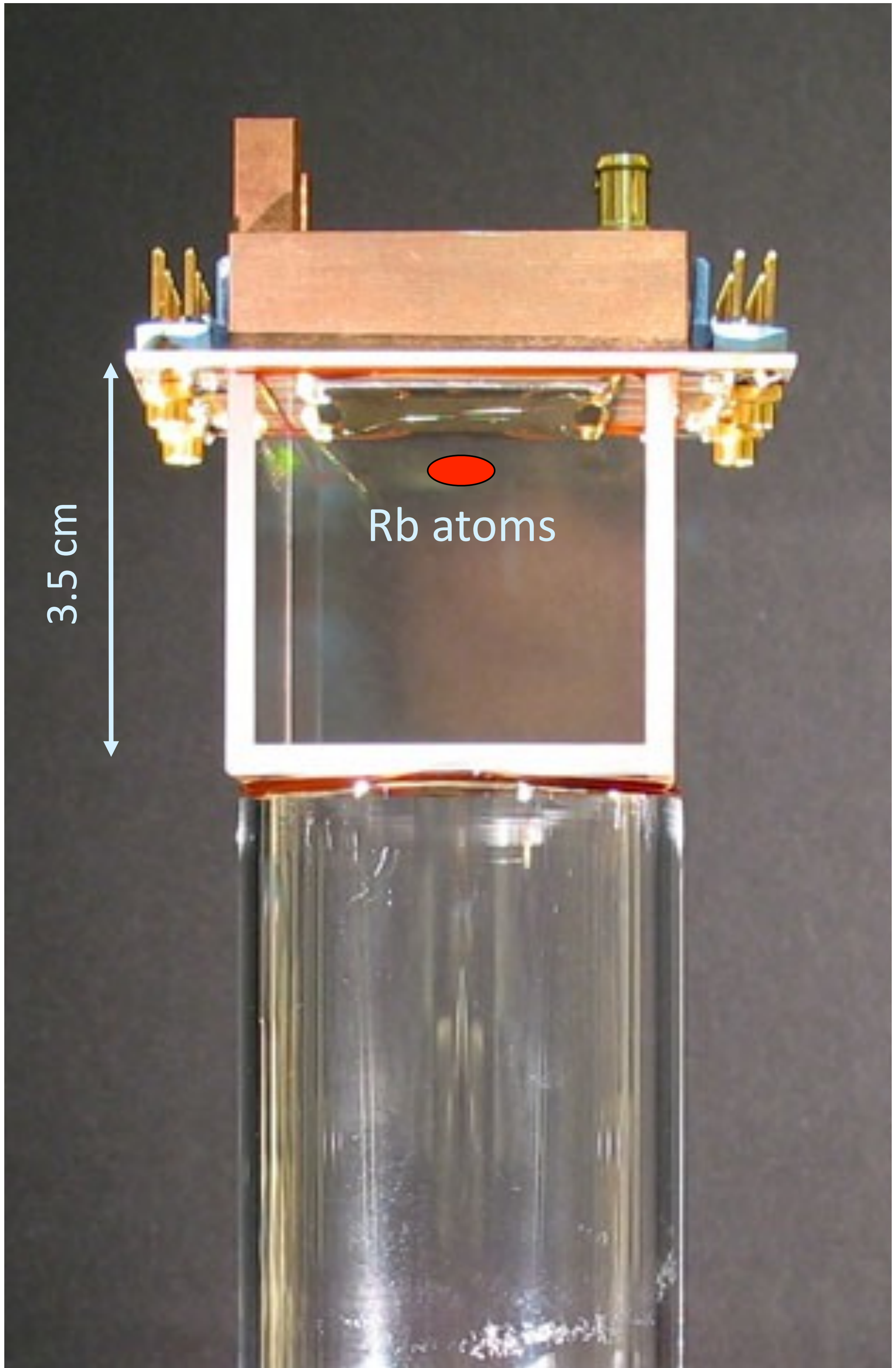
cooling laser beam



- mirror-MOT
- optical molasses
- optical pumping
- magnetic trap
- transport atoms
- evaporative cooling to Bose-Einstein condensation

Laser cooling

ultra-high vacuum
3×10^{-10} mbar



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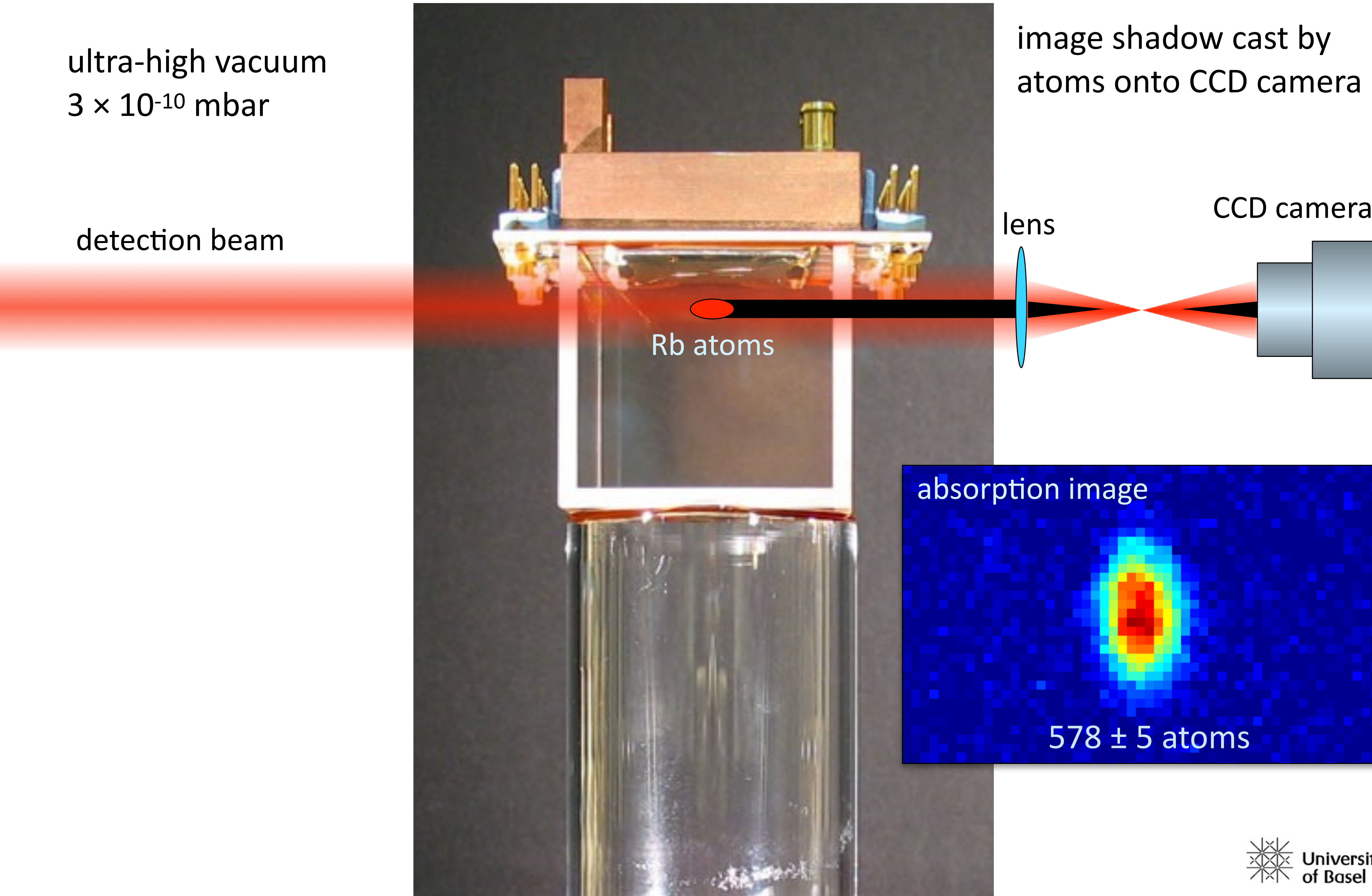
Detection: absorption imaging

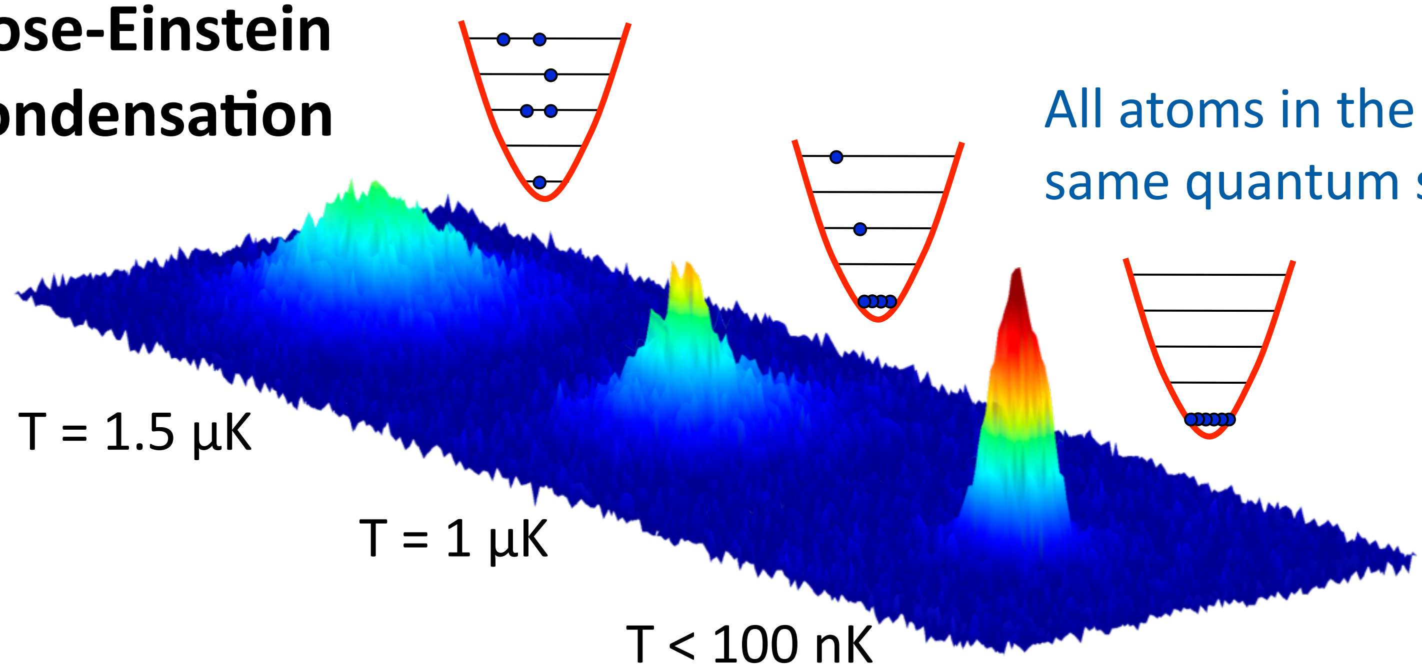
ultra-high vacuum
3×10^{-10} mbar

image shadow cast by atoms onto CCD camera



Two-component BEC of ^{87}Rb atoms

Bose-Einstein condensation



All atoms in the same quantum state

Quantum control of
- **internal state**
- **motion**
- **collisions**

Böhi et al., Nature Physics 5, 592 (2009)

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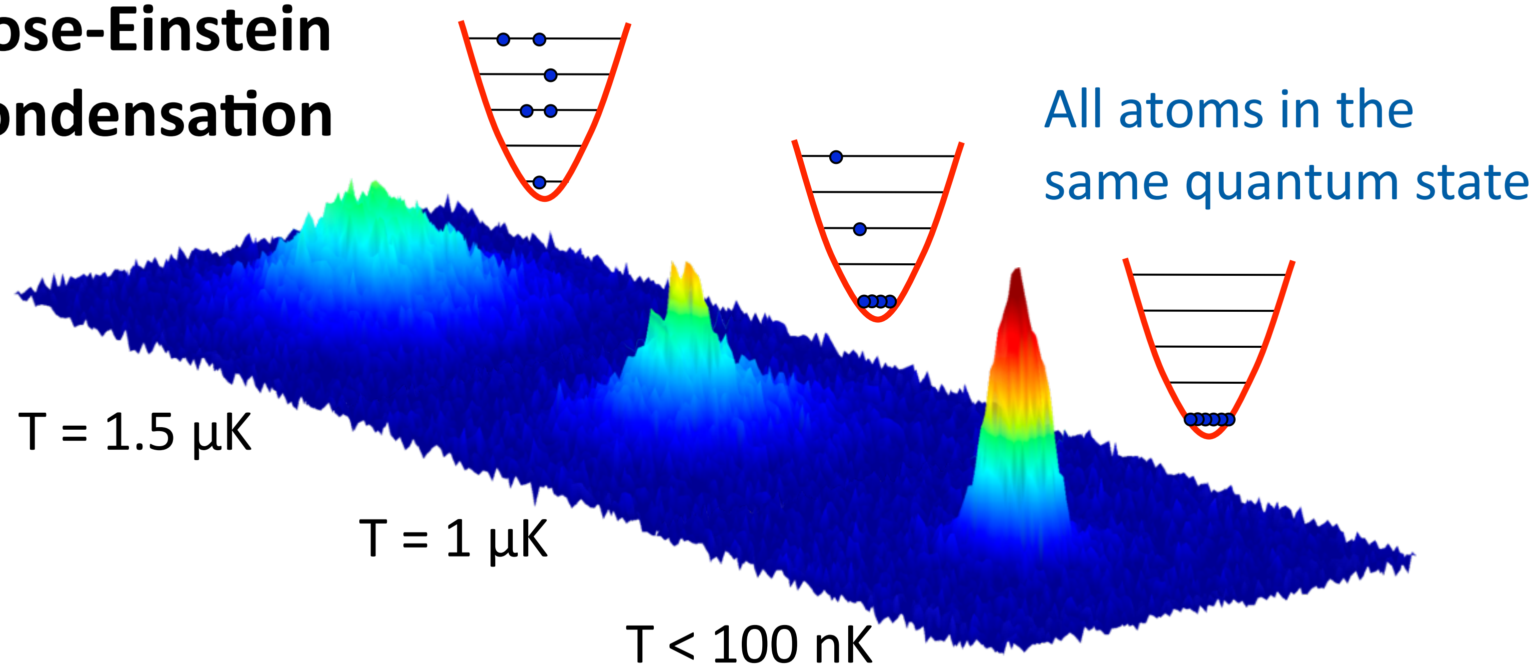

Quantum control of
- **internal state**
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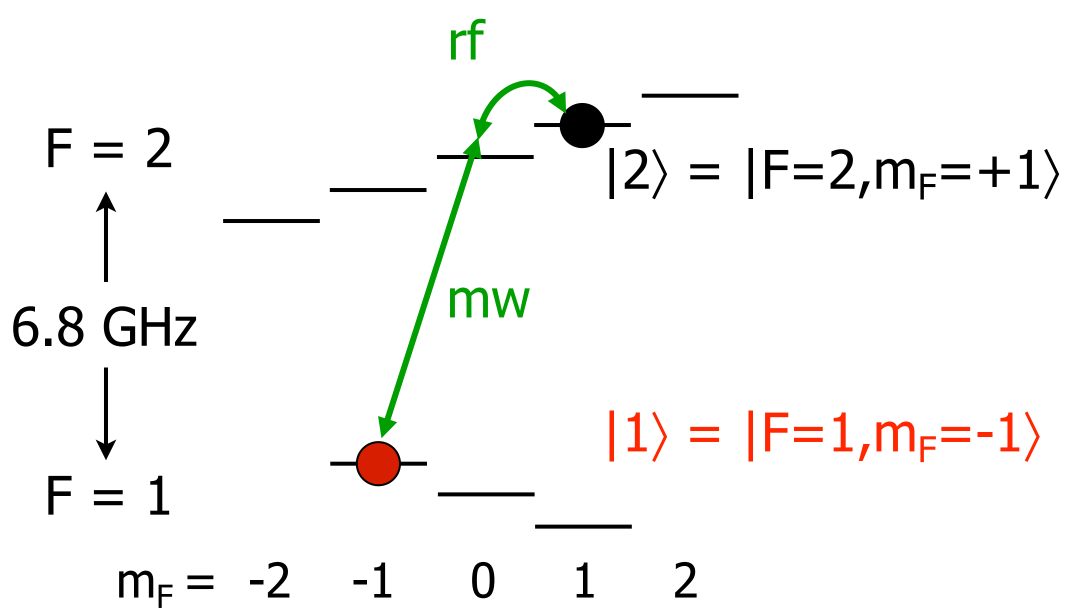
^{87}Rb ground-state hyperfine structure



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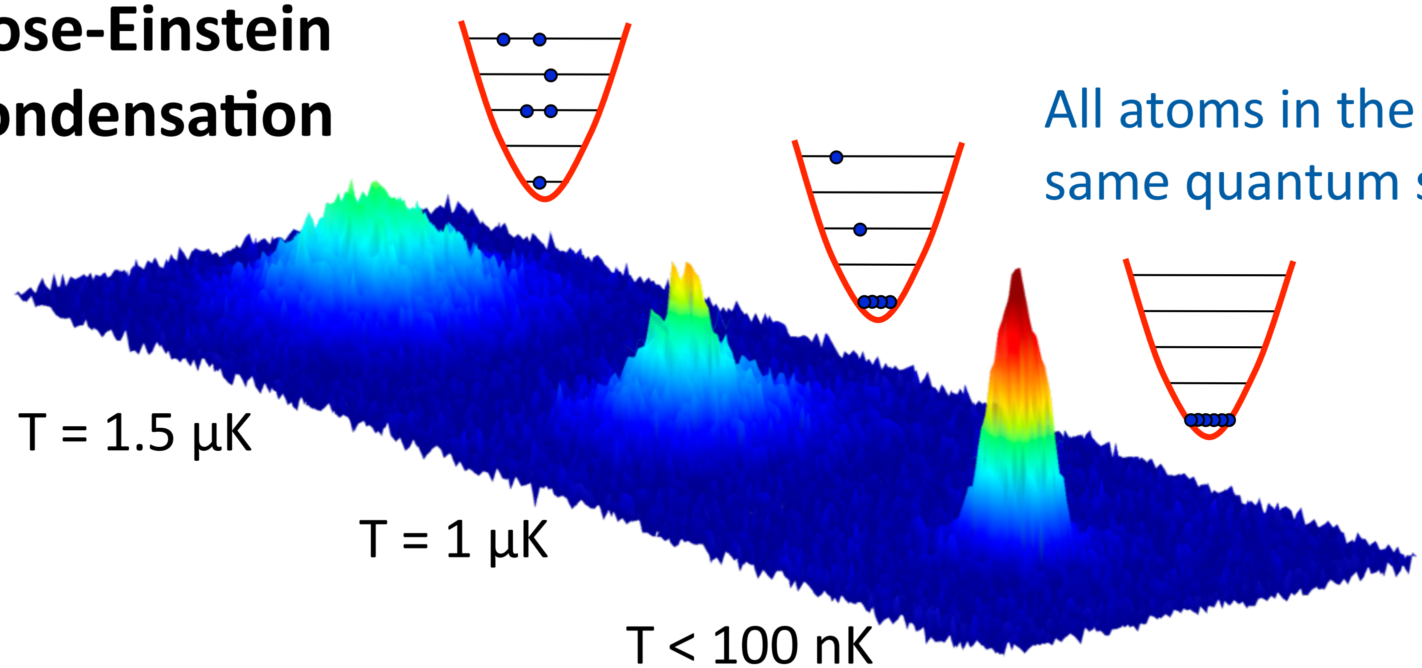

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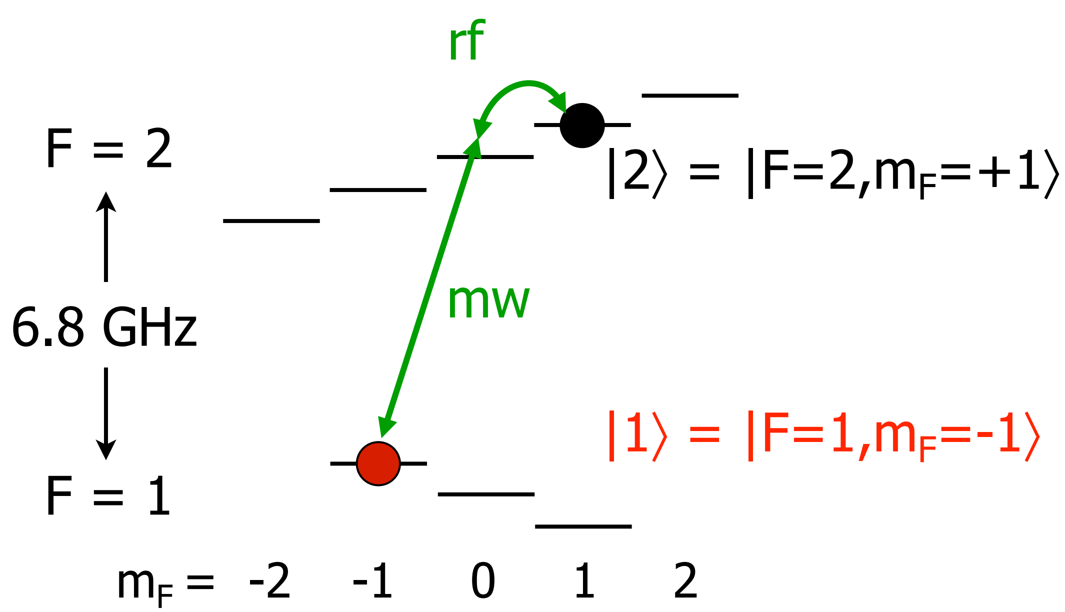
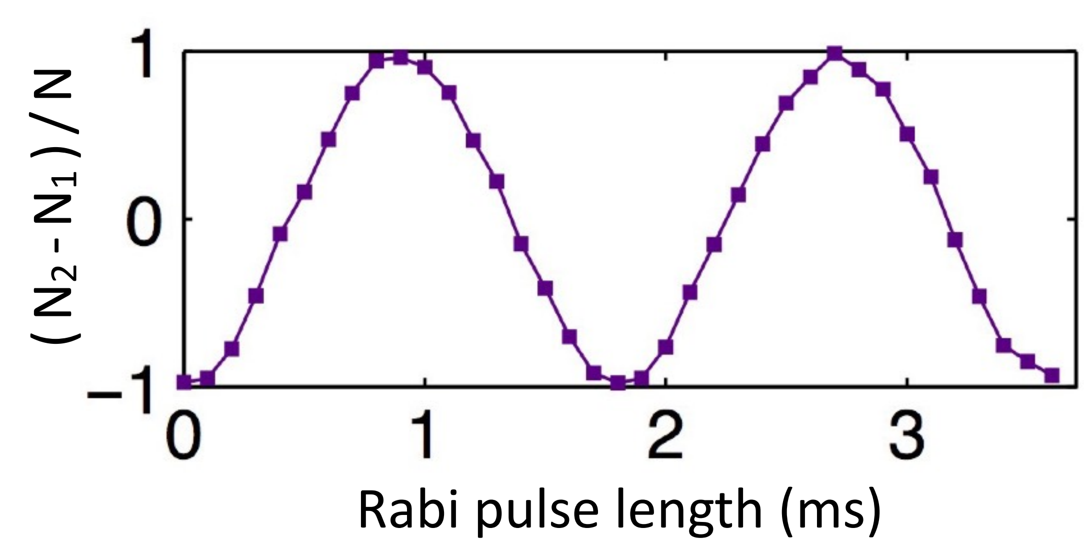


Rabi oscillations

fidelity of $\pi/2$-pulse: (99.74±0.04) %



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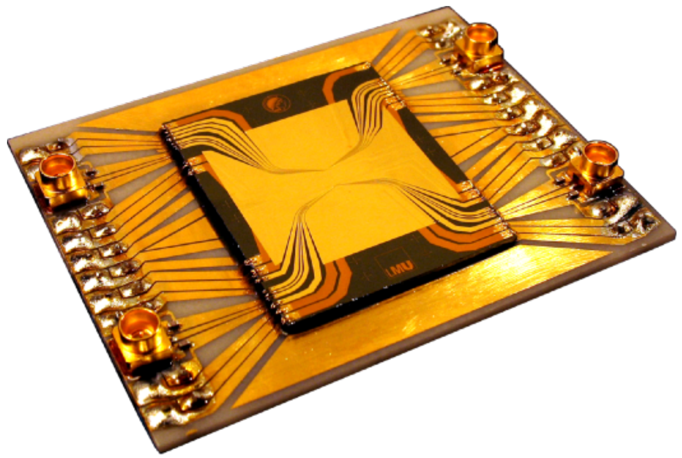
Outline



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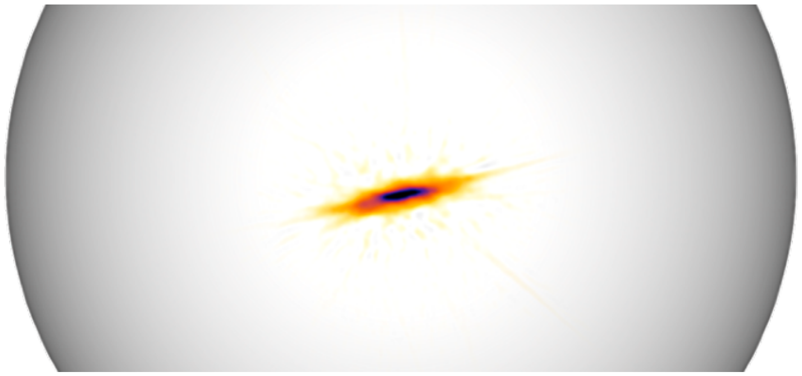

Spin-squeezed states for quantum metrology

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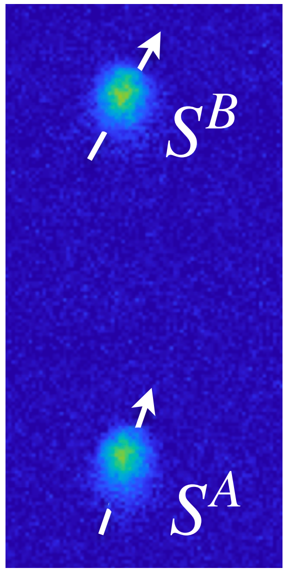
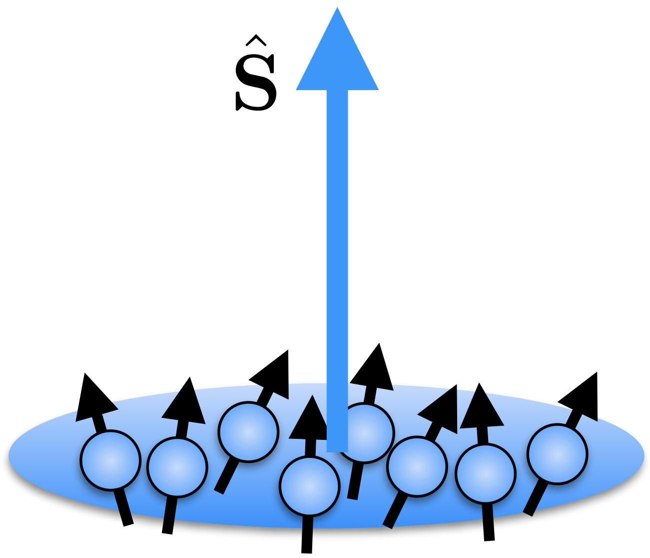


Entanglement, EPR and Bell correlations

Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)

Perspectives for searches of new physics

Spin-squeezing through atomic interactions

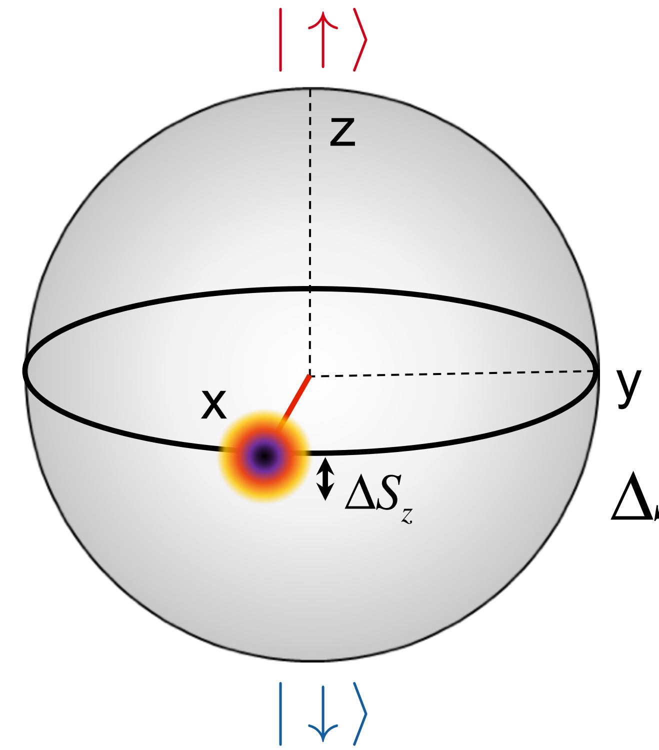


Ensemble of spins

Collective spin

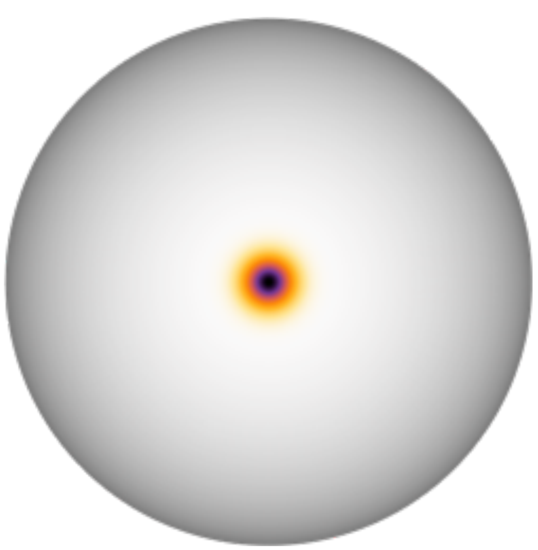
$$\hat{\mathbf{S}} = \sum_{i=1}^{N} \hat{\mathbf{s}}_i, \quad S = \frac{N}{2}$$

$$\hat{S}_z = \frac{1}{2}(\hat{N}_\uparrow - \hat{N}_\downarrow)$$



$$\Delta S_z = \frac{\sqrt{N}}{2}$$

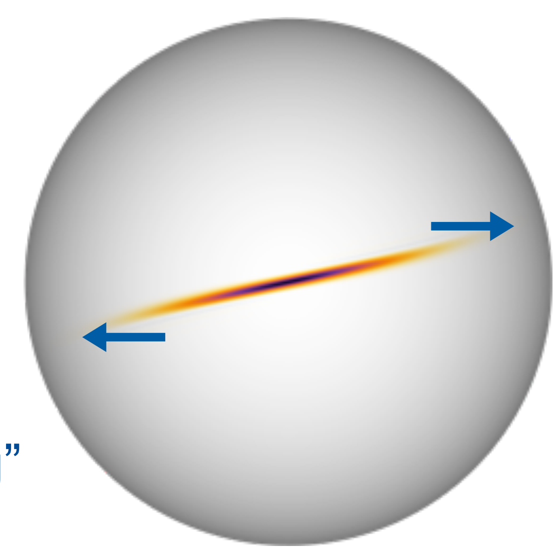
Atomic collisions create spin-squeezing



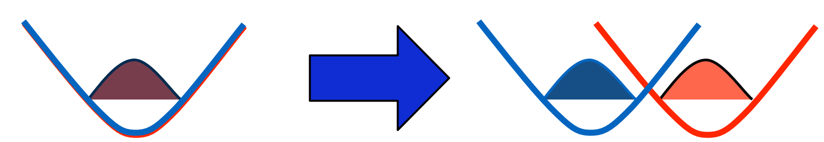
coherent spin state

$$\hat{\mathcal{H}} = \chi \hat{S}_z^2$$

time evolution
“one-axis twisting”



squeezed spin state



interaction tuning by
state dependent potentials

Riedel et al, Nature 464, 1170 (2010)

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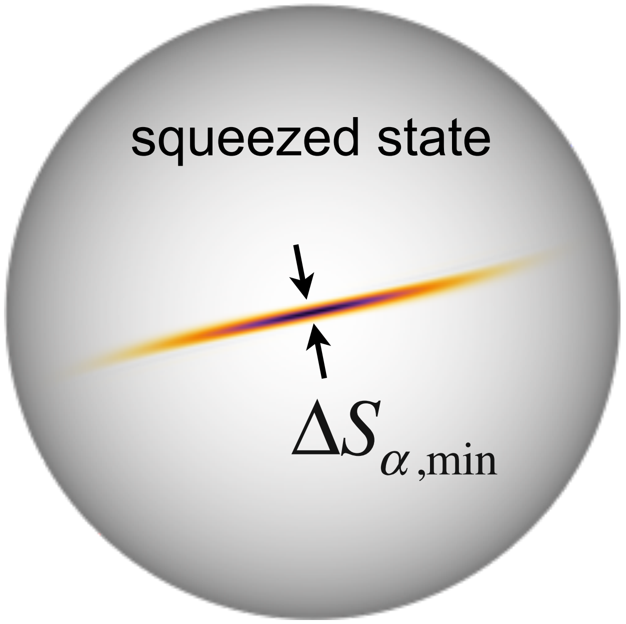
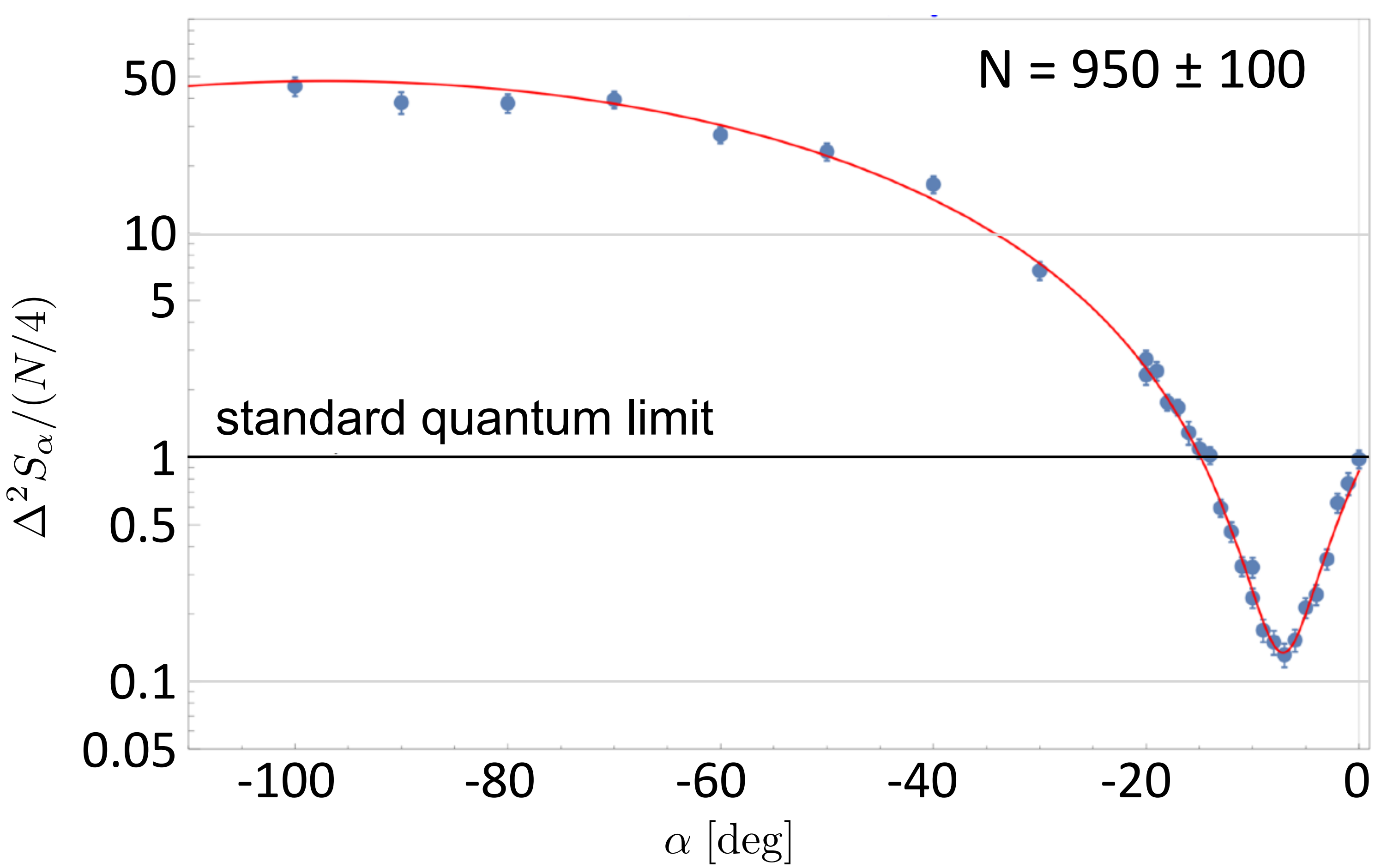
Tomography of spin-squeezed state



$\xi^2 < 1$



Spin-squeezing parameter

$$\xi^2 \equiv \frac{N\left(\Delta S_{\alpha,\min}\right)^2}{\left\langle S_x \right\rangle^2}$$

entanglement witness

Kitagawa & Ueda PRA 47, 5138,1993
Wineland et al. PRA 50, 67,1994
Sørensen et al. Nature 409, 63–66, 2001

ξ^2 = -8.2 ± 0.5 dB
⇒ entanglement

(Noise reduced by -8.7 ± 0.5 dB, contrast C = 94.9%)

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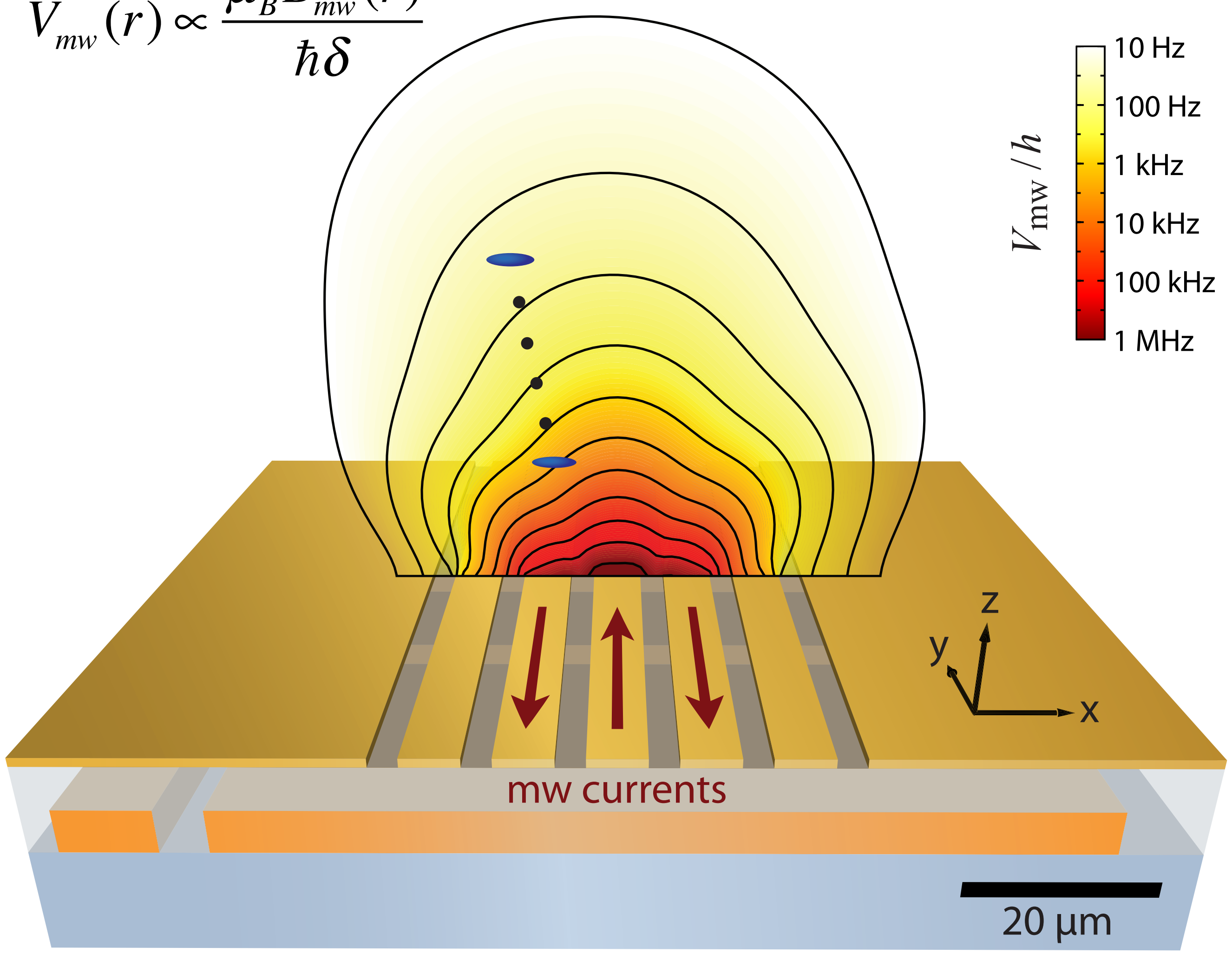
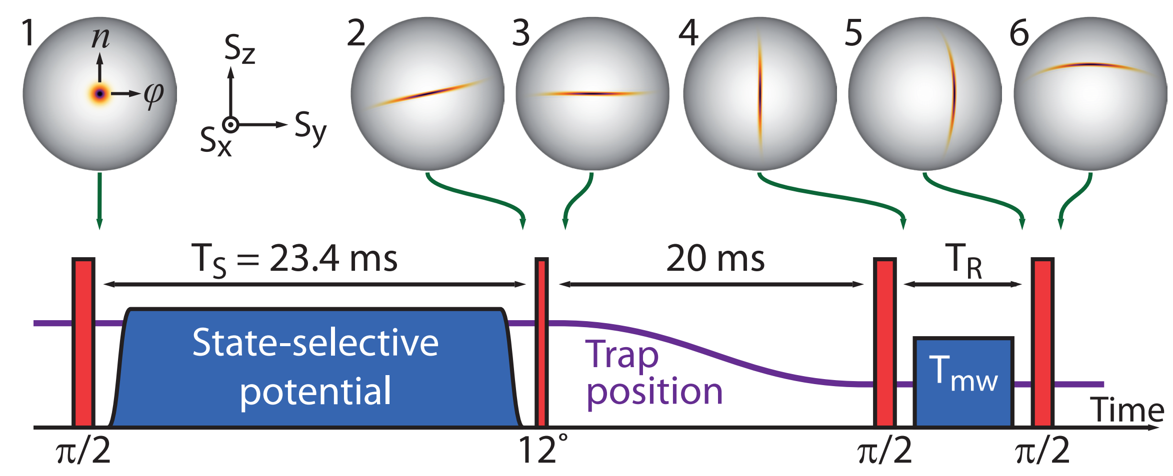
Microwave field measurement beyond the SQL

$$V_{mw}(r) \propto \frac{\mu_B^2 B_{mw}^2(r)}{\hbar\delta}$$



Ramsey sequence with spin-squeezed state



C. Ockeloen et al, PRL 111, 143001 (2013)

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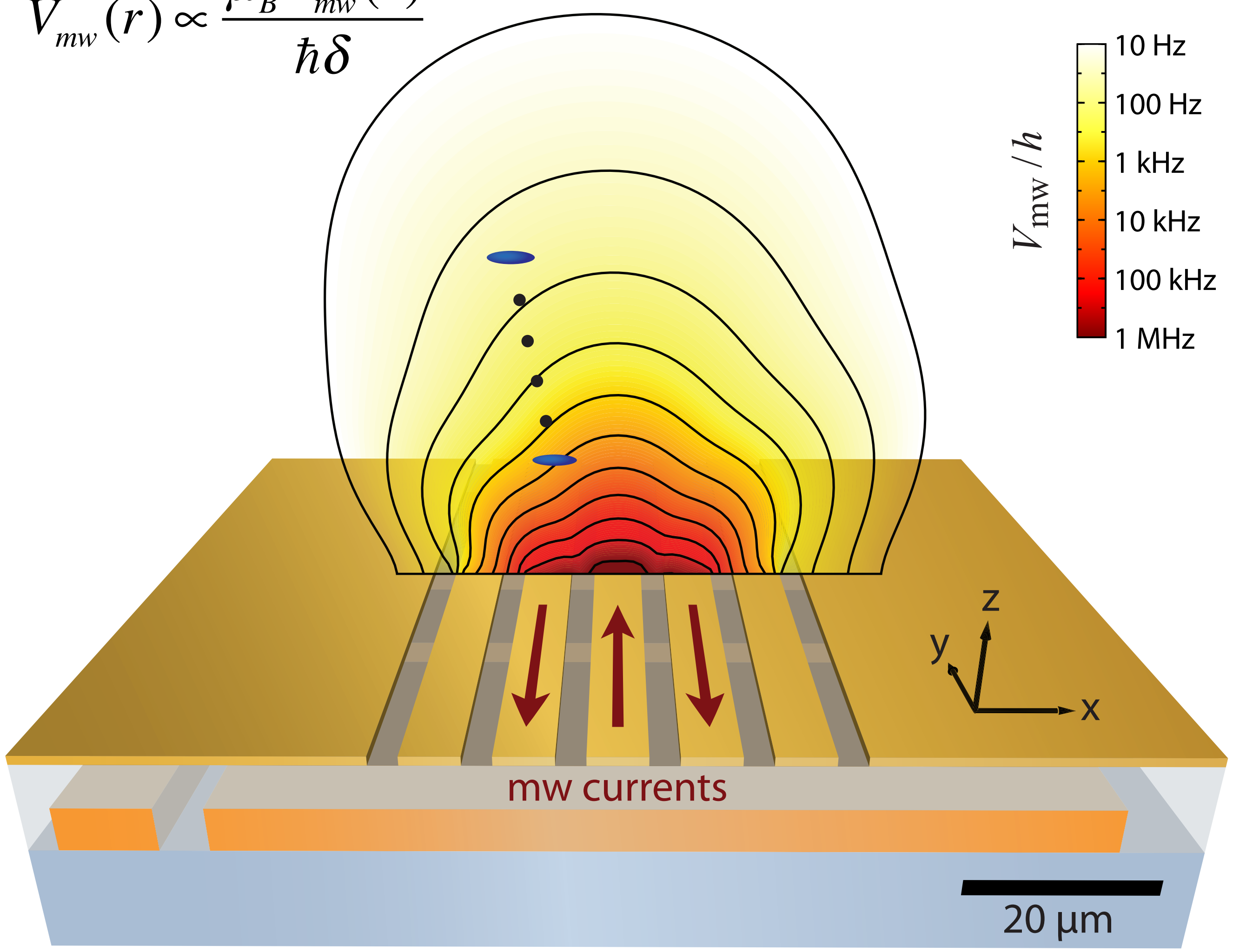

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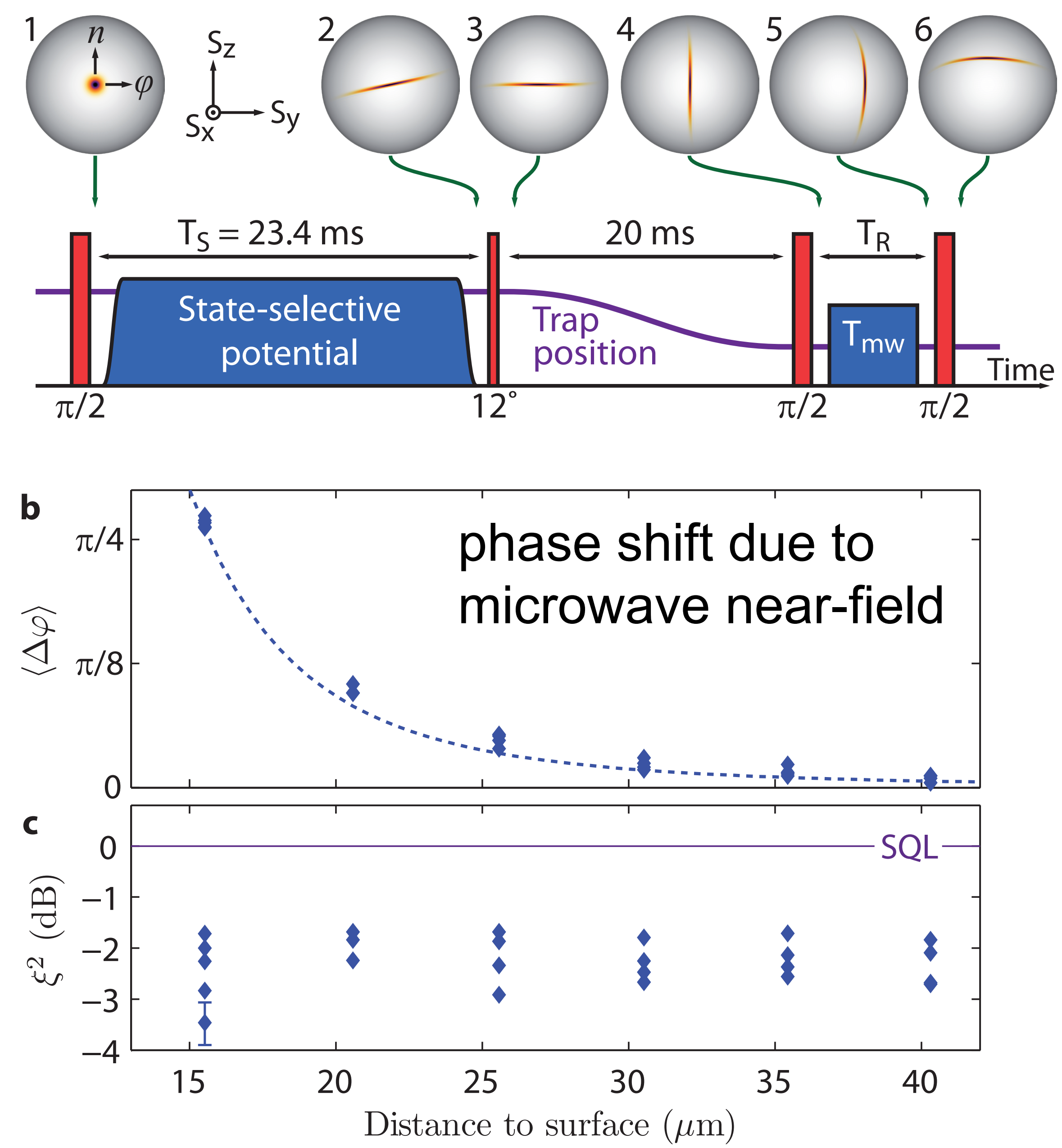

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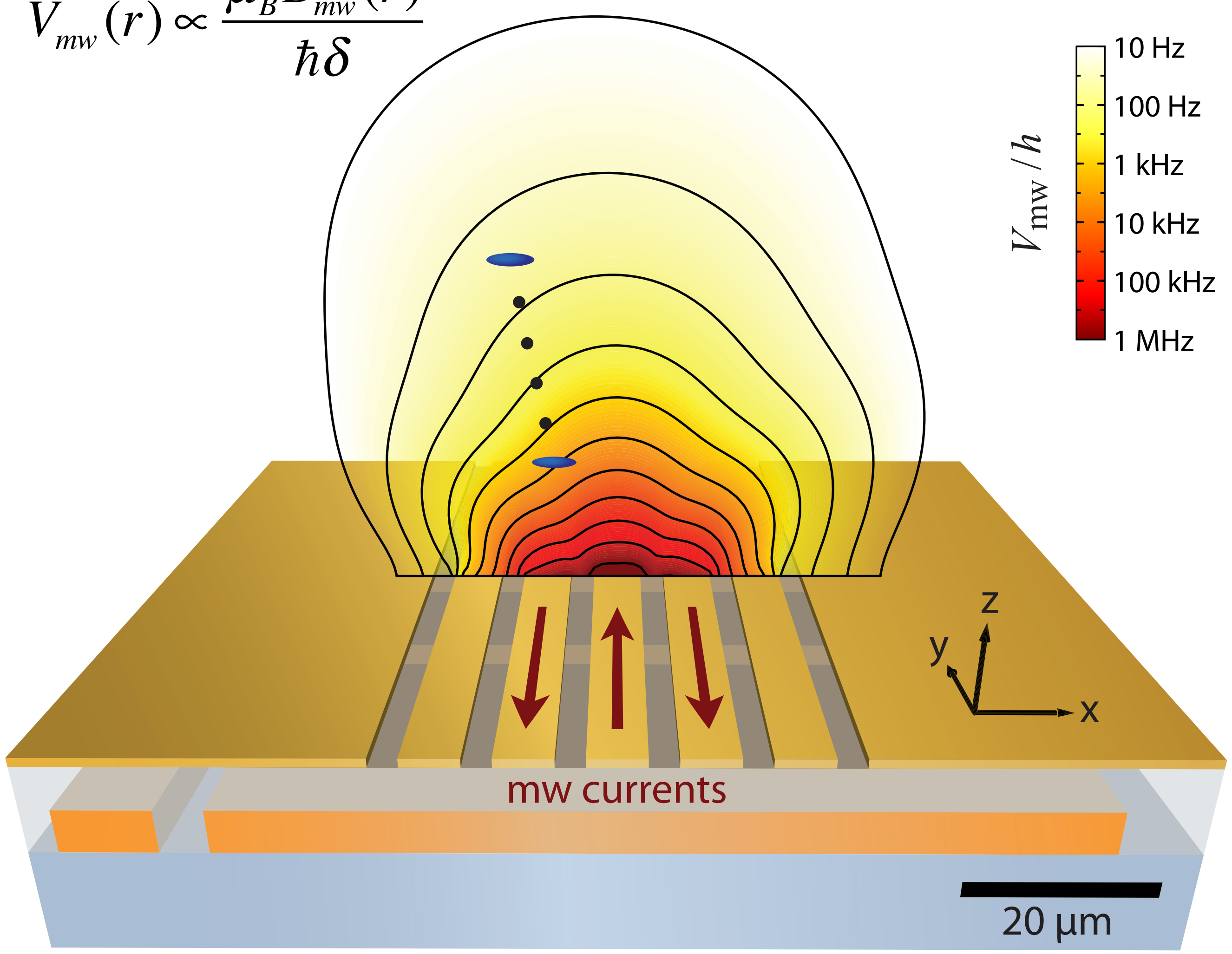
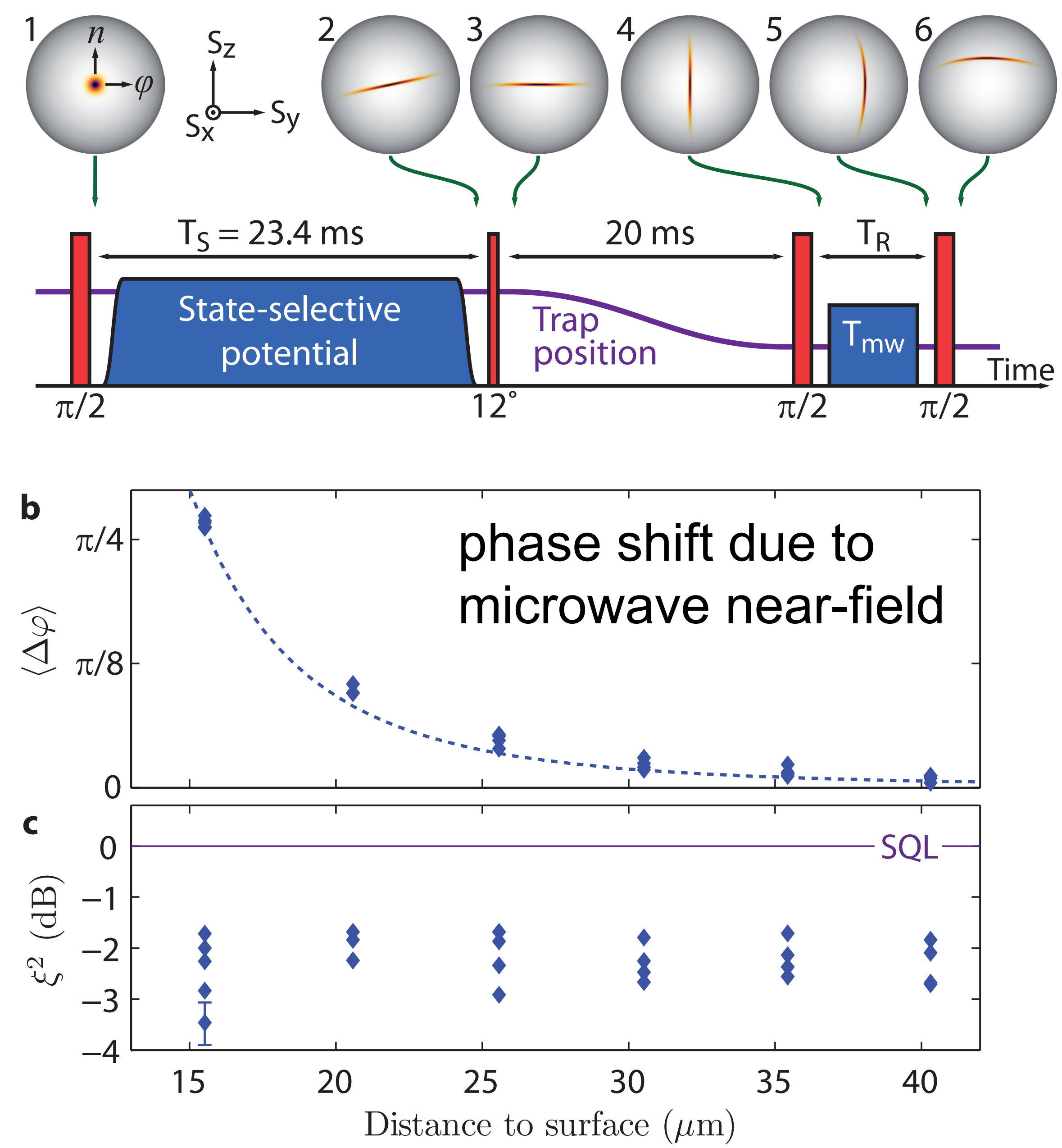


Sensitivity:

δB_{mw} = 77 pT @ 1 s
(near-resonant mw field)

Probe volume: 20 µm³

Ramsey sequence with spin-squeezed state



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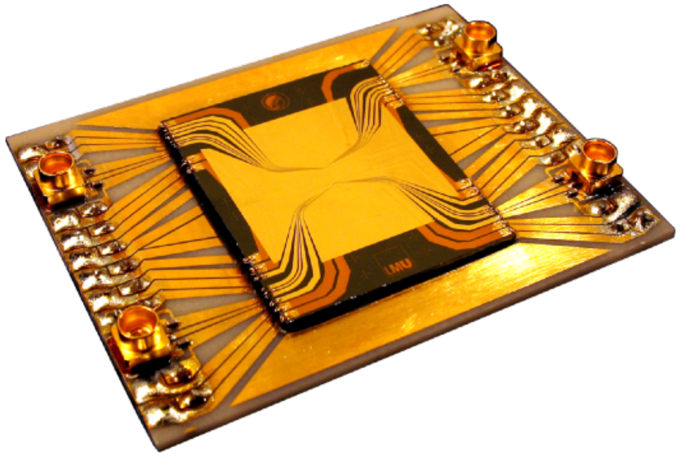
Outline



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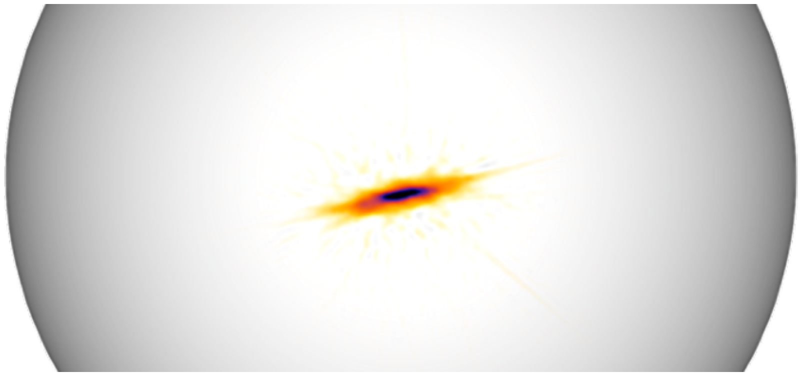

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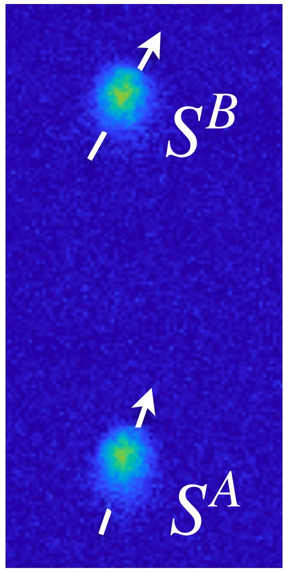
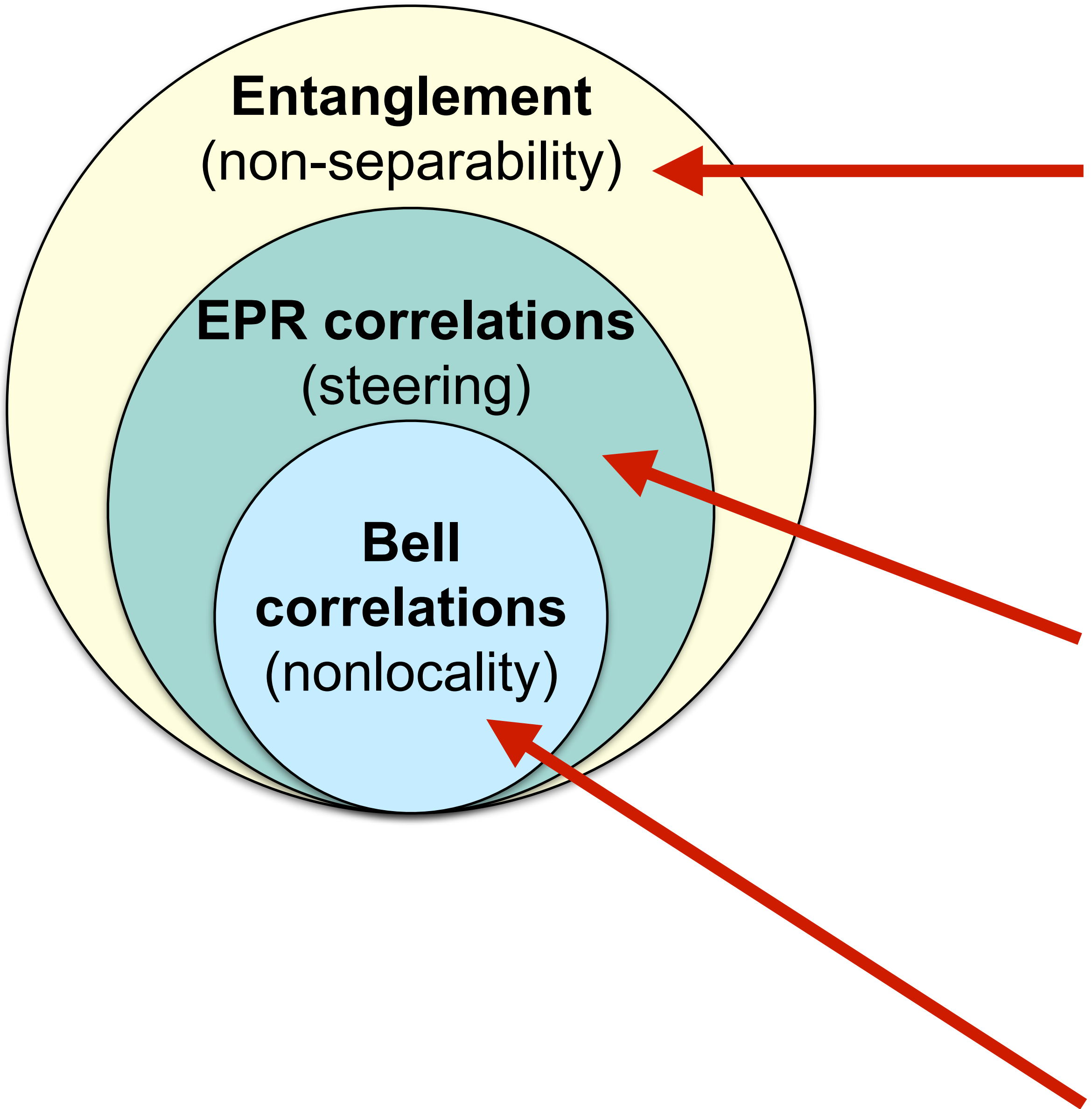


Entanglement, EPR and Bell correlations

Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)

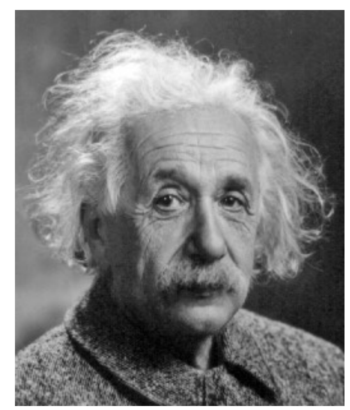
Perspectives for searches of new physics

Hierarchy of non-classical correlations



Erwin Schrödinger

Mathematical Proceedings of the Cambridge Philosophical Society 31, 555 (1935)



Albert Einstein

Boris Podolsky

Nathan Rosen

Physical Review 47, 777 (1935)

John Stewart Bell

Physics 1, 195 (1964)

Gühne and Tóth, Phys. Rep. 474, 1 (2009)
Reid et al, Rev. Mod. Phys. 81, 1727 (2009)
Brunner et al, Rev Mod Phys 86, 419 (2014)

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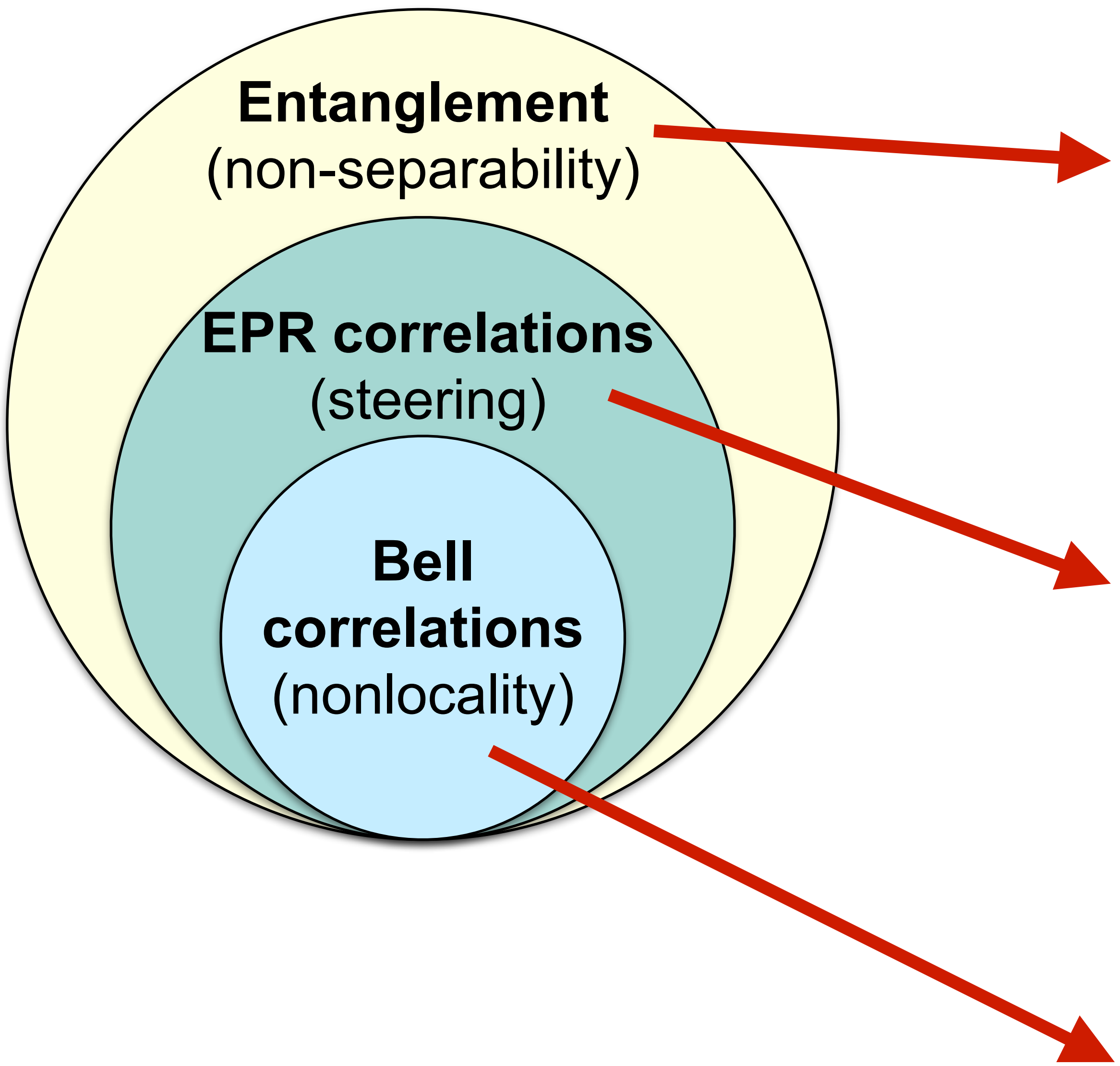
Correlations as a resource for quantum technology



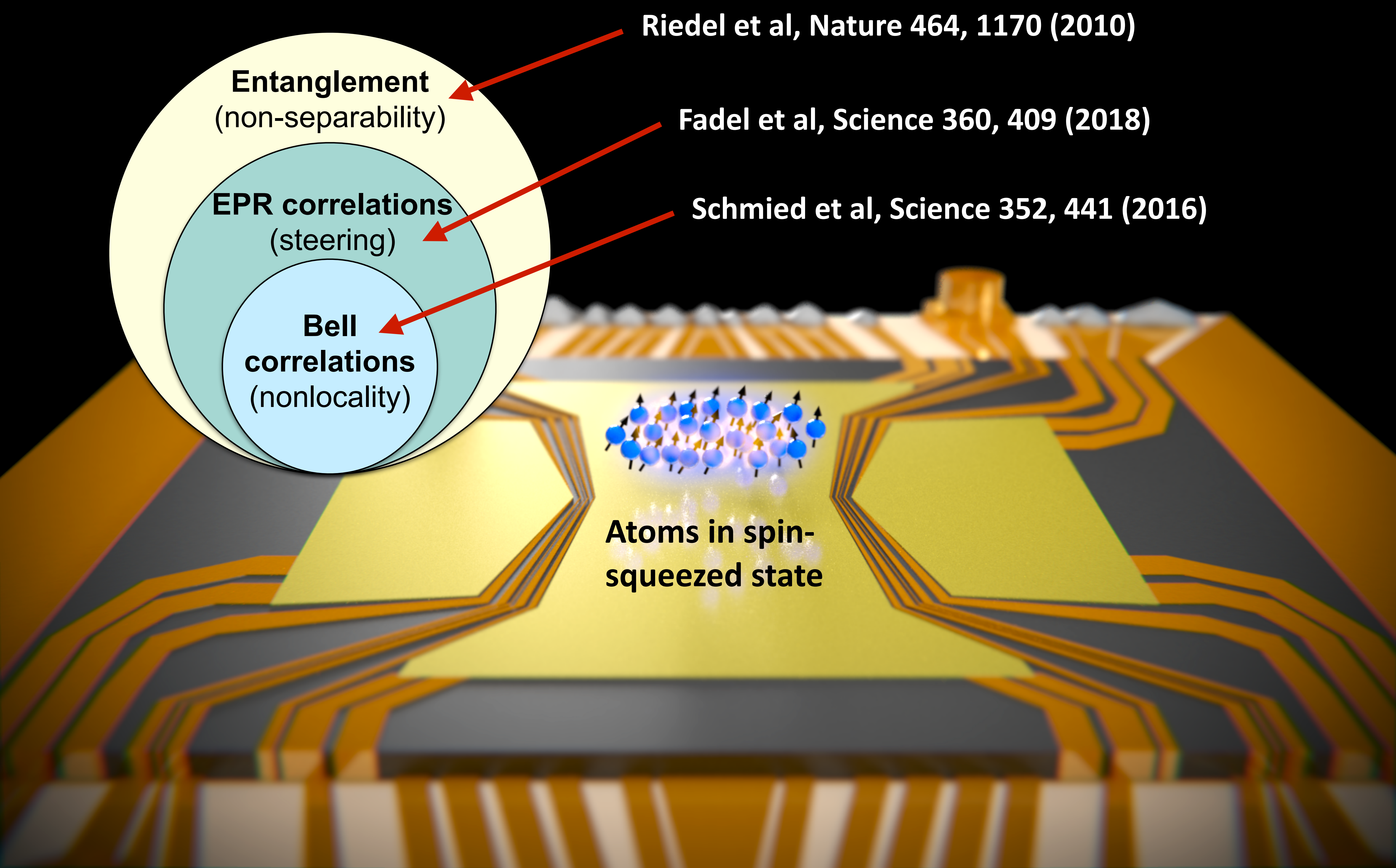
- Interferometry beyond the standard quantum limit
- QIP with trusted devices

- Quantum teleportation
- Remote state preparation
- One-sided device-independent QKD
- Certain quantum metrology tasks

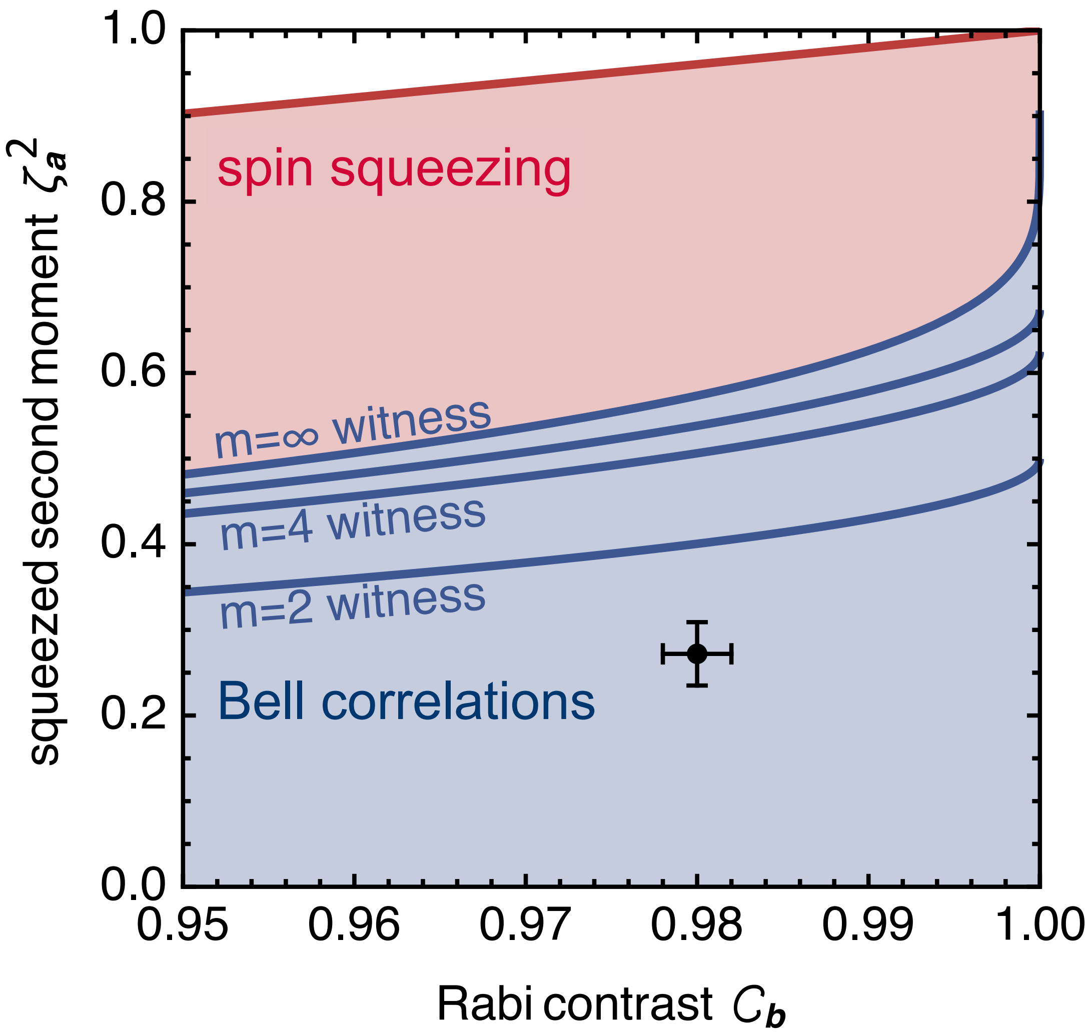
- Device-Independent QKD
- Certified randomness generation
- Self-testing of states and measurements

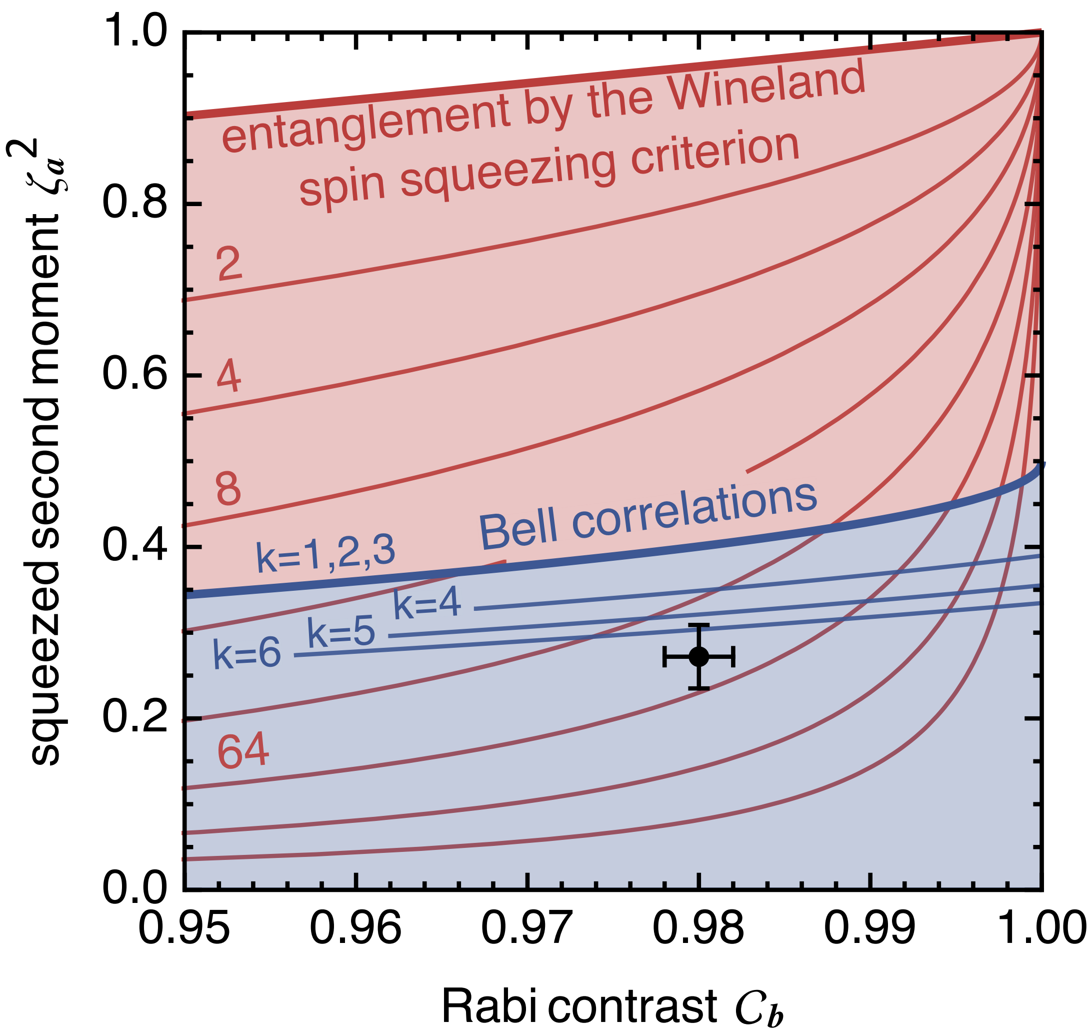
Gühne and Tóth, Phys. Rep. 474, 1 (2009)
Reid et al, Rev. Mod. Phys. 81, 1727 (2009)
Brunner et al, Rev Mod Phys 86, 419 (2014)

Non-classical correlations in many-body systems



Multi-partite Bell correlations





Bell witness derived from Bell inequality with m measurement settings and taking m → ∞

$$\zeta_a^2 \geq 1 - \frac{\mathcal{C}_b}{\operatorname{arctanh}\left[\mathcal{C}_b\right]}$$

Wagner et al, PRL 119, 170403 (2017)
Schmied et al, Science 352, 441 (2016)

Genuine multi-partite Bell correlations!

Based on k-partite Bell inequalities with up to 2nd order correlators

Baccari et al, PRA 100, 022121 (2019)

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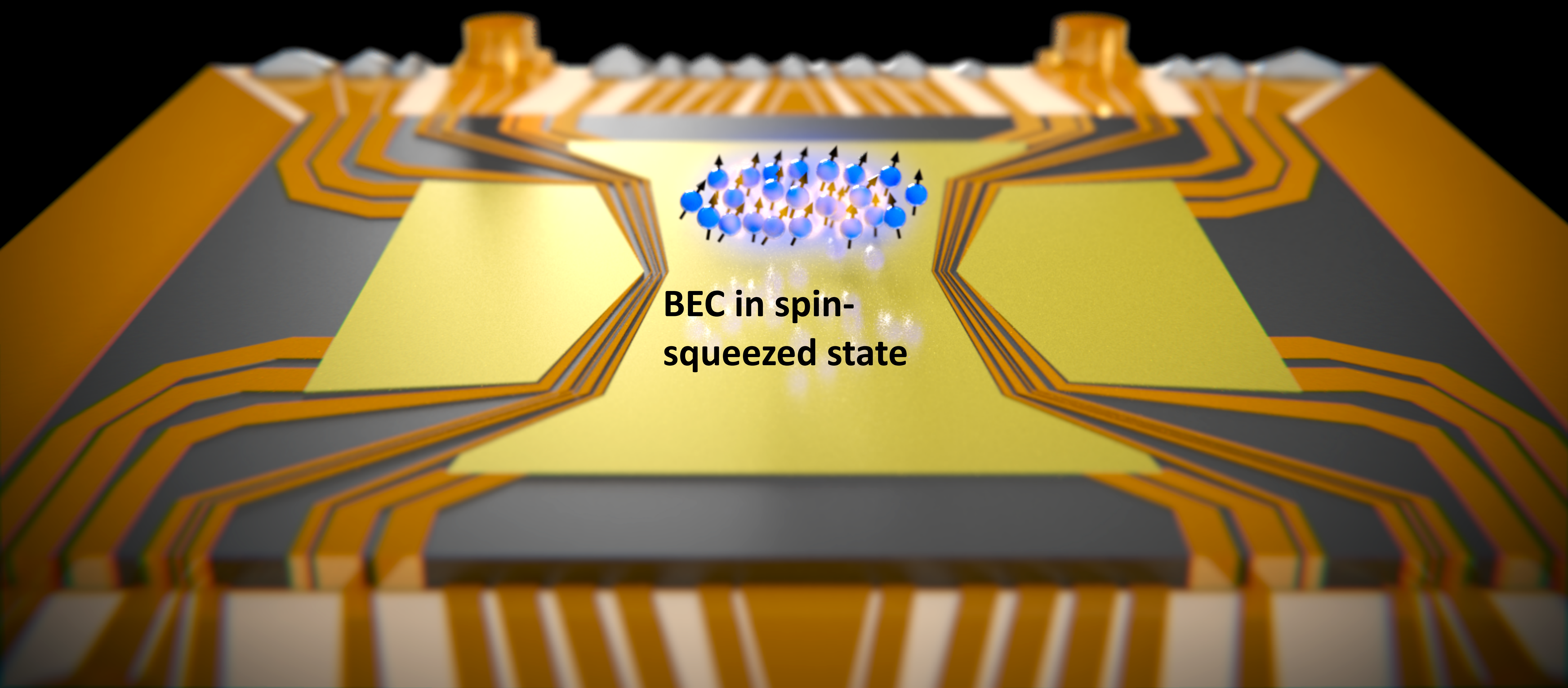
Spatial splitting of spin-squeezed BEC



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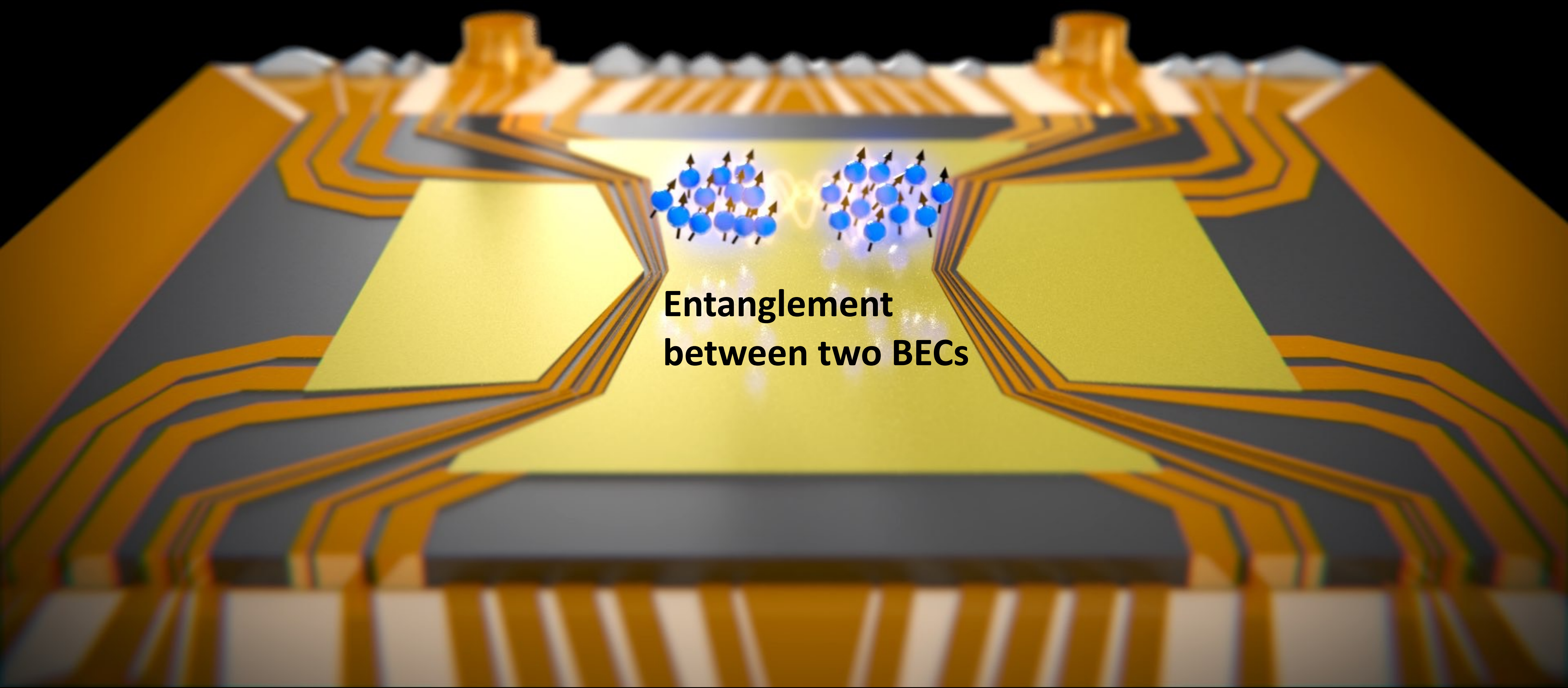
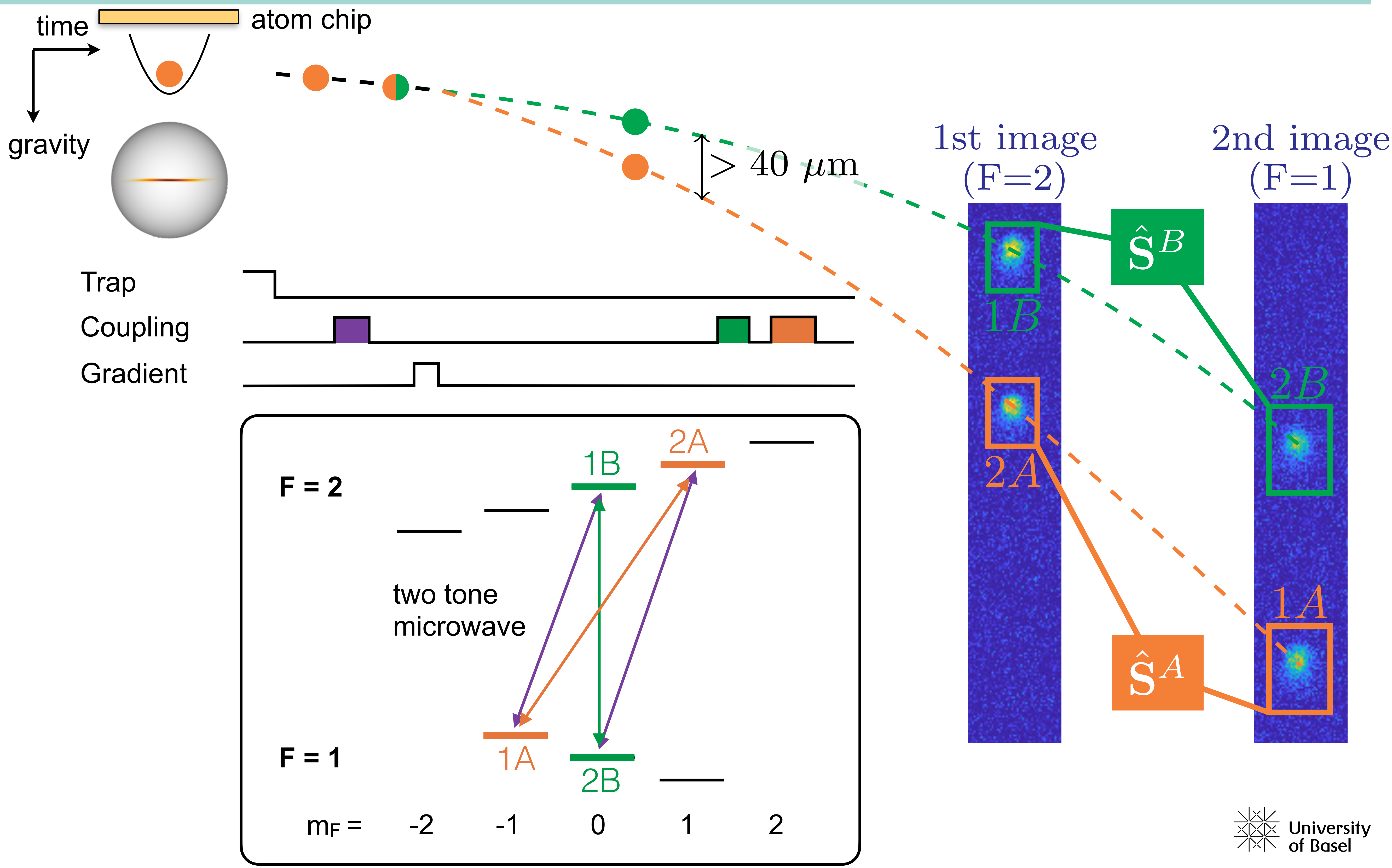


Coherent spatial splitting of BEC



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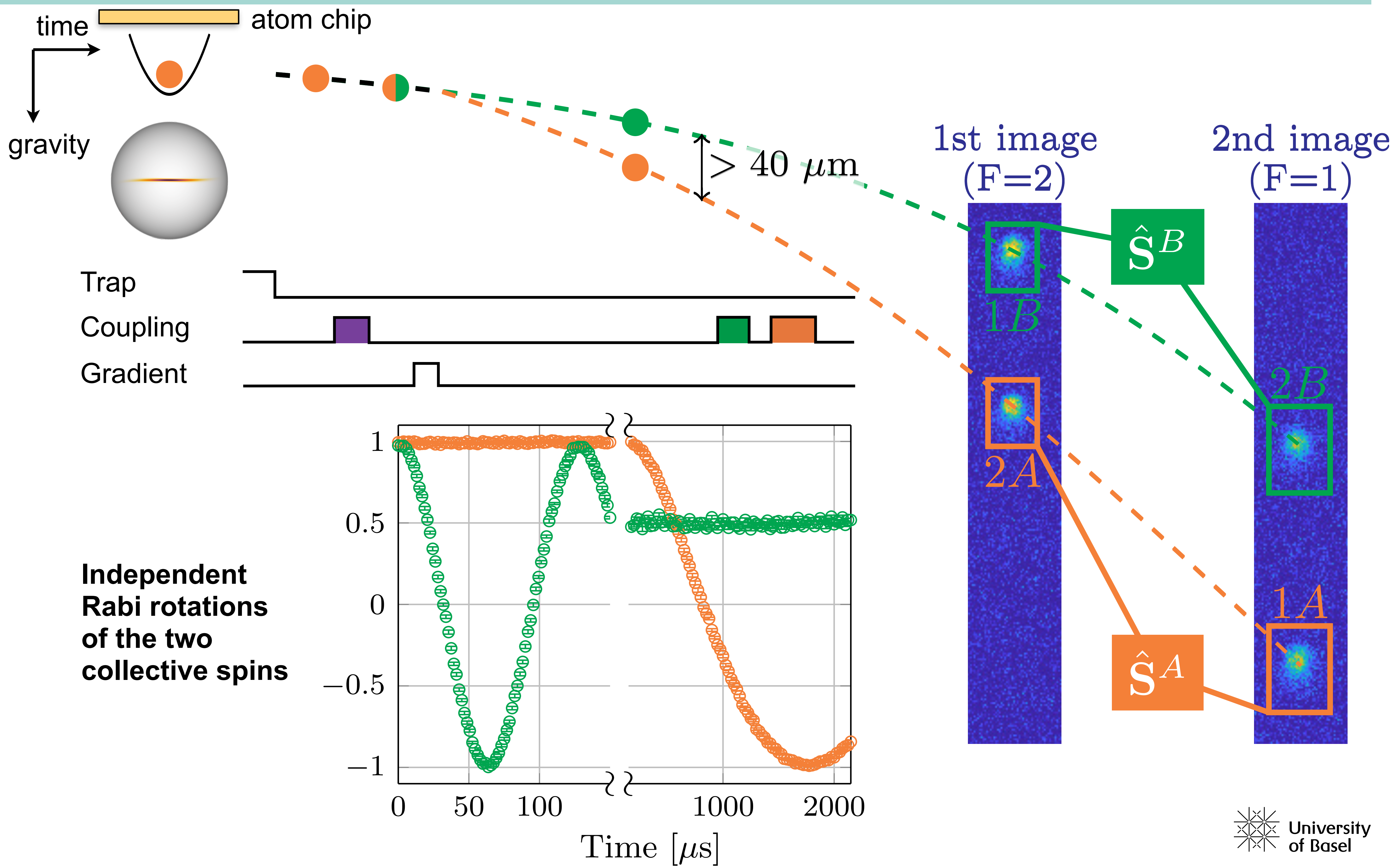
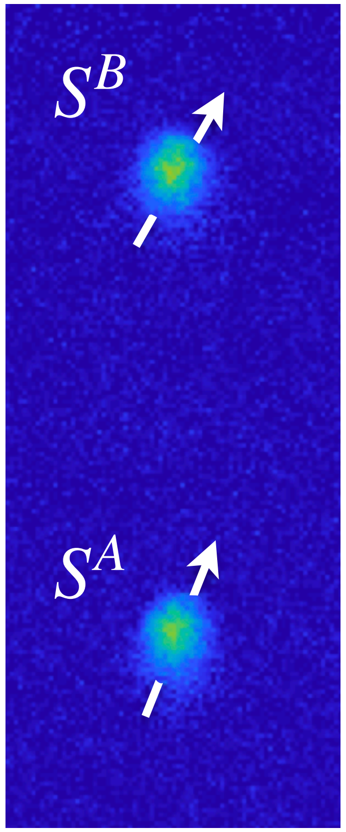
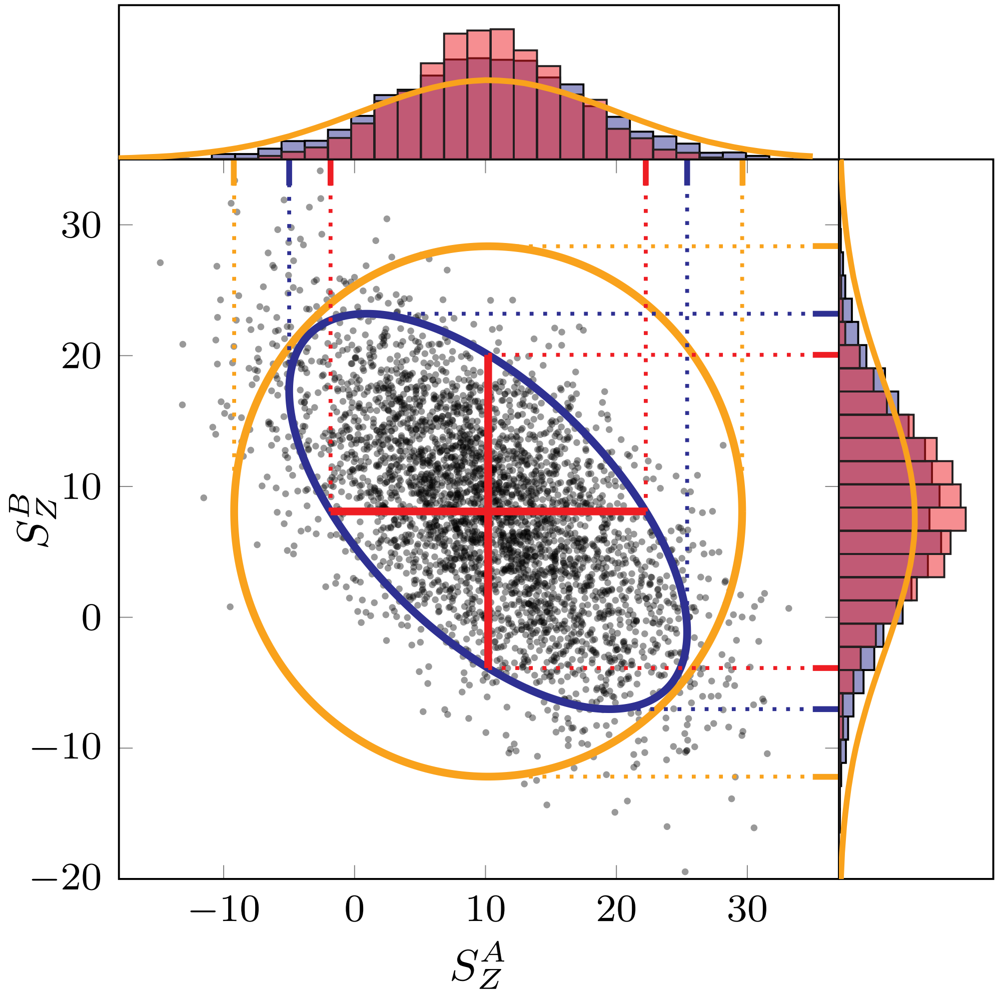
Independent spin rotations after splitting

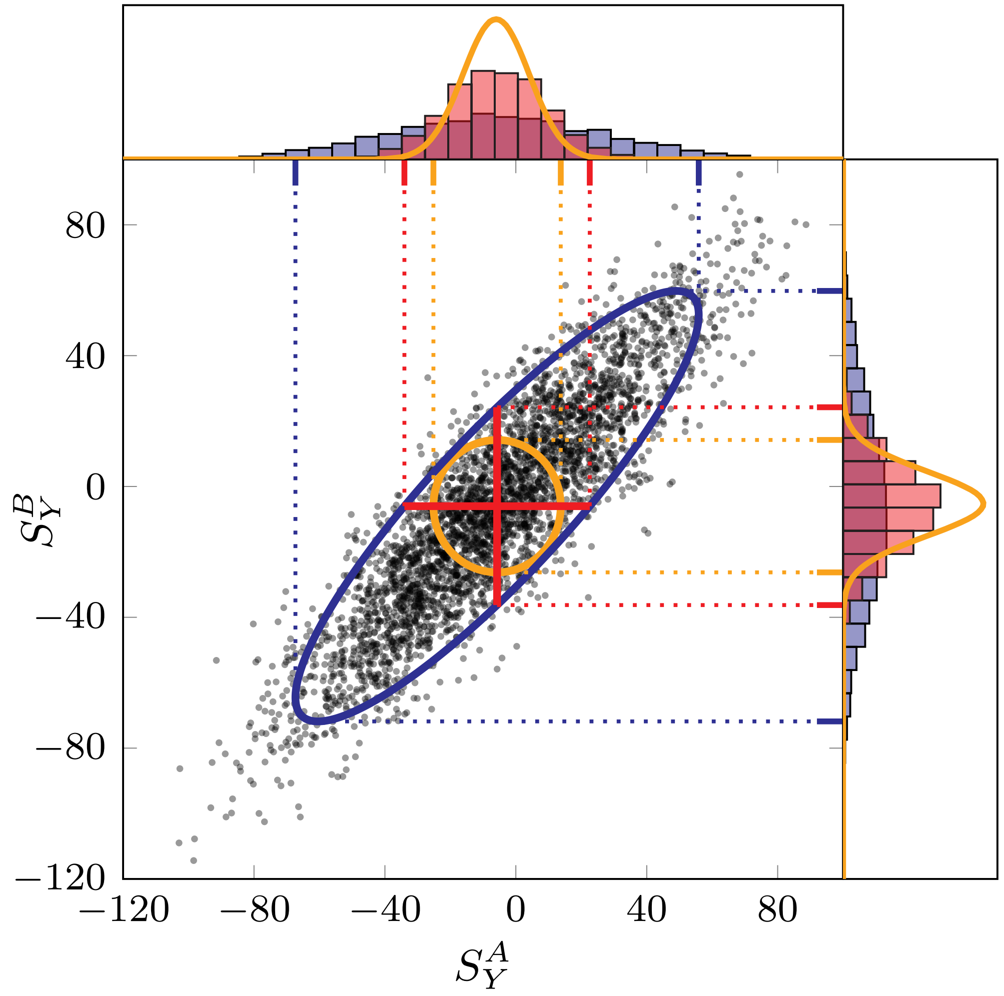


Independent Rabi rotations of the two collective spins

Entanglement between spatially separated BECs







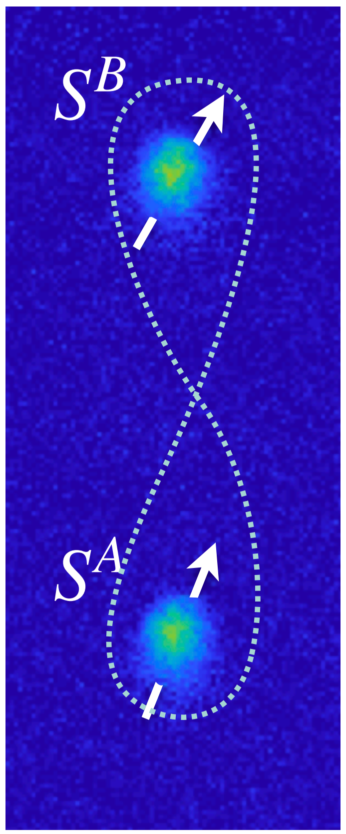
- $N \approx 900$ atoms
- initial squeezing $\xi^2 \approx -7\,\mathrm{dB}$
- split spins are still squeezed
- contrast in S_x^A and S_x^B about 94%

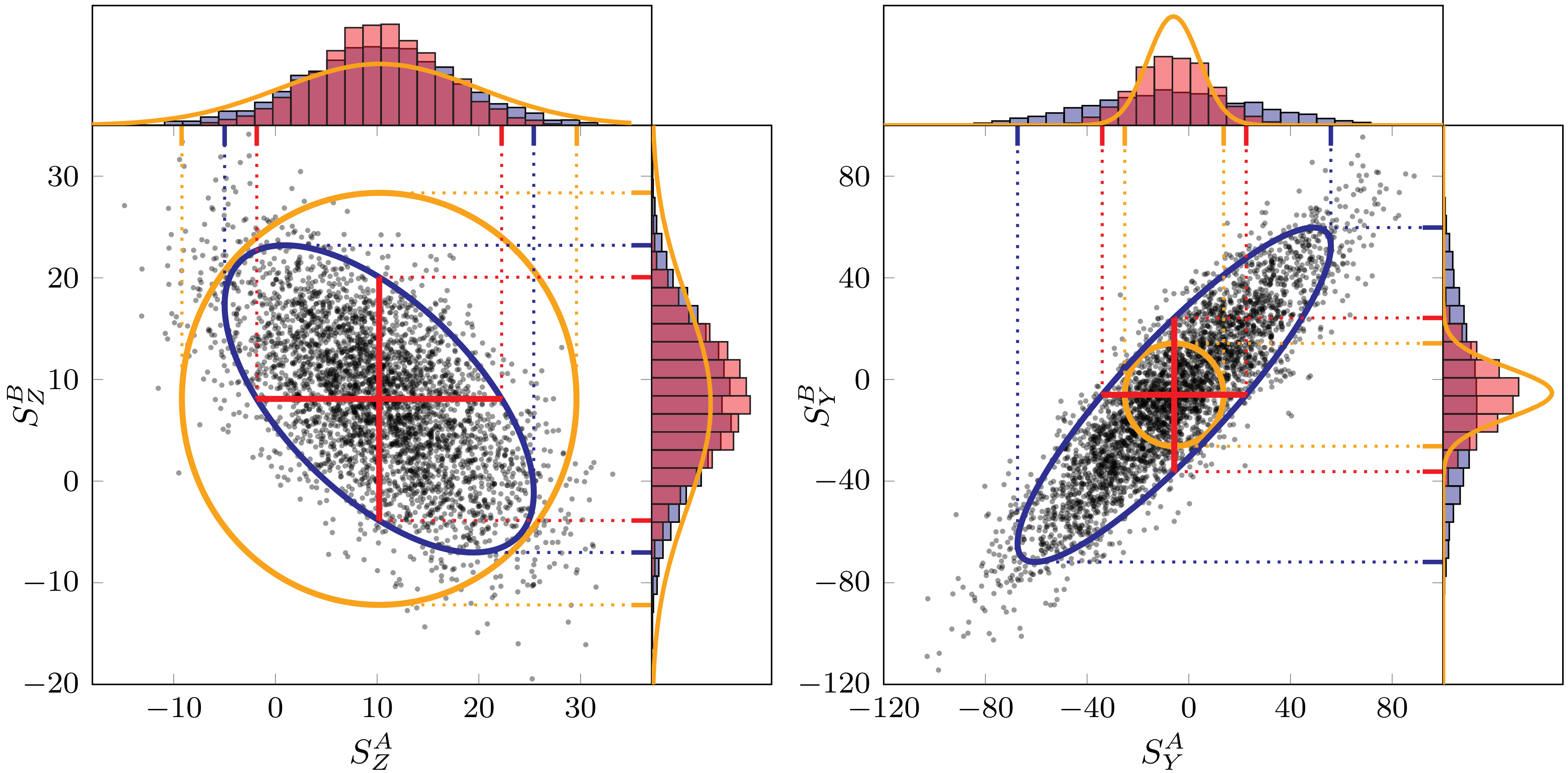
Entanglement criterion

$$E_{Ent} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y \hat{S}_y^A\right)\mathrm{Var}\left(\hat{S}_z^B - g_z \hat{S}_z^A\right)}{\left(|\langle \hat{S}_x^B \rangle| + |g_y g_z||\langle \hat{S}_x^A \rangle|\right)^2} = 0.51(2) < 1$$

Giovannetti et al, PRA 67, 022320 (2003)

Entanglement between spatially separated BECs





- $N \approx 900$ atoms
- initial squeezing $\xi^2 \approx -7\,\mathrm{dB}$
- split spins are still squeezed
- contrast in S_x^A and S_x^B about 94%

Entanglement criterion

$$E_{Ent} = \frac{4\,\mathrm{Var}\left(\hat{S}_y^B - g_y \hat{S}_y^A\right)\mathrm{Var}\left(\hat{S}_z^B - g_z \hat{S}_z^A\right)}{\left(|\langle \hat{S}_x^B \rangle| + |g_y g_z||\langle \hat{S}_x^A \rangle|\right)^2} = 0.51(2) < 1$$

Giovannetti et al, PRA 67, 022320 (2003)

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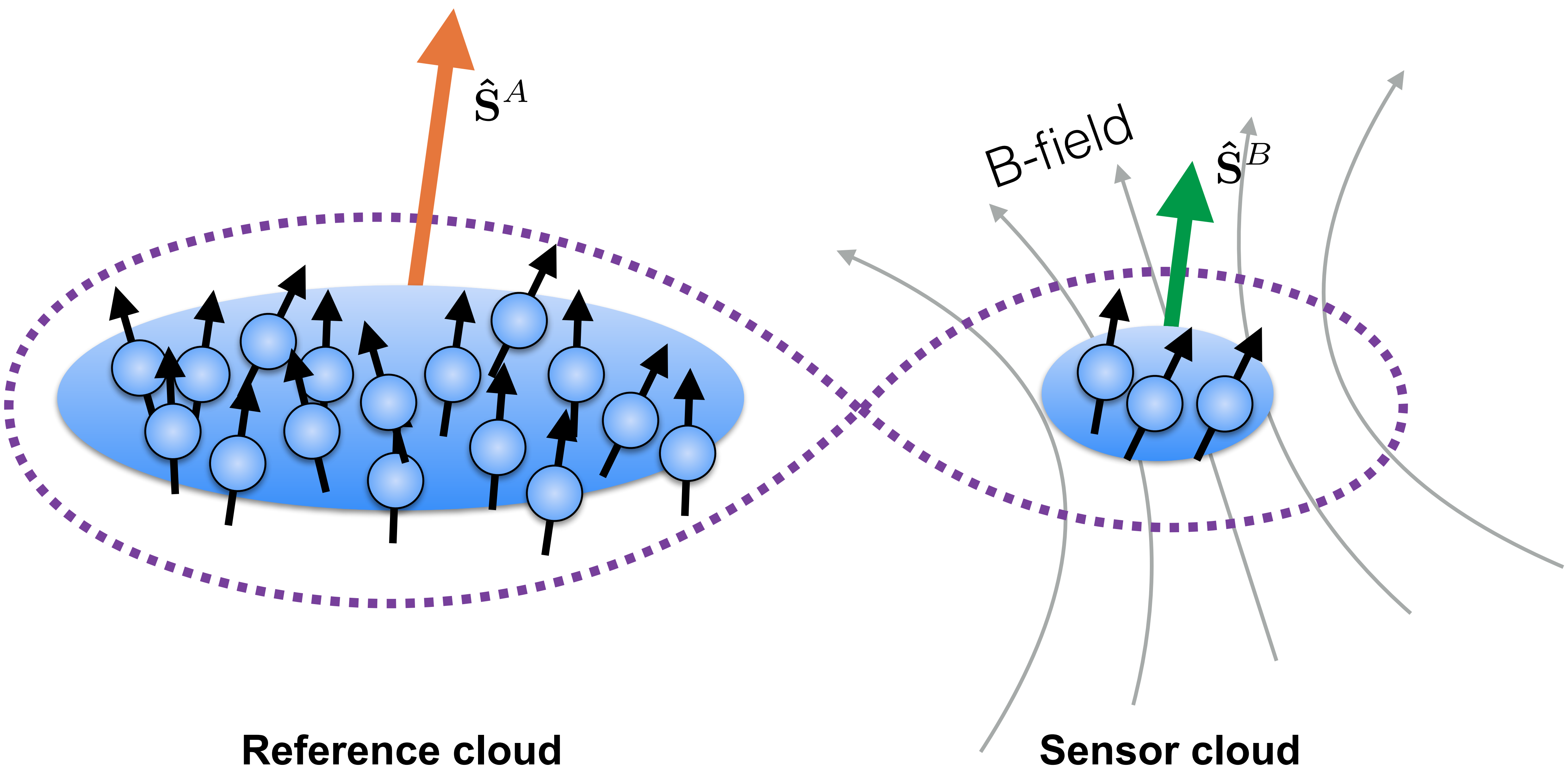
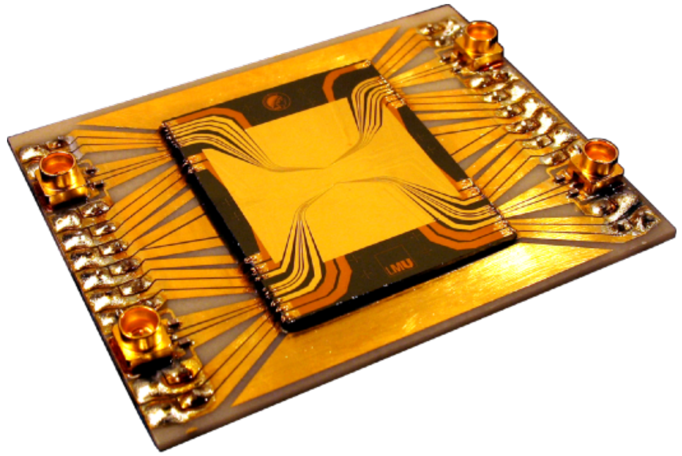
Quantum enhanced measurements with entangled BECs



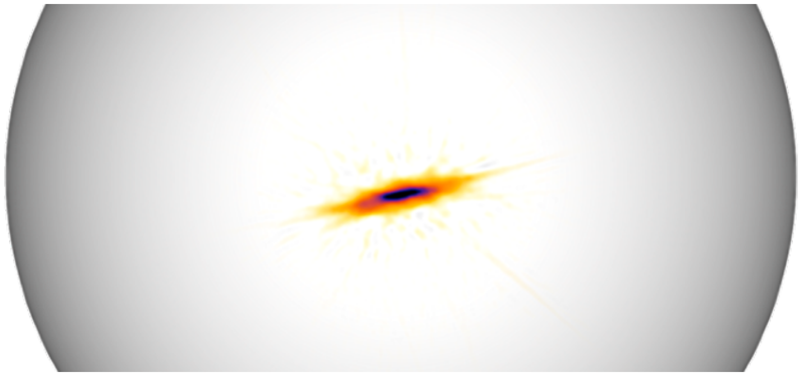
- small sensor size leads to projection noise
- entanglement with large reference cloud improves measurement

Outline



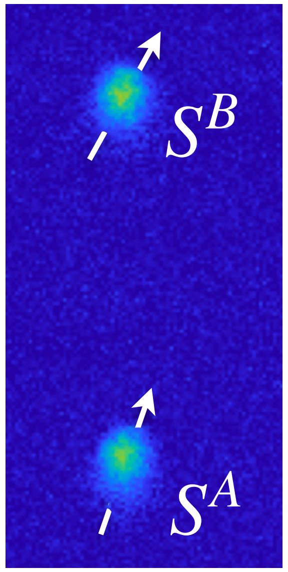
Ultracold atoms on atom chips

Treutlein et al, Phys Rev Lett 92, 203005 (2004)
Böhi et al, Nature Physics 5, 592 (2009)



Spin-squeezed states for quantum metrology

Riedel et al, Nature 464, 1170 (2010)
Ockeloen et al, PRL 111, 143001 (2013)



Entanglement, EPR and Bell correlations

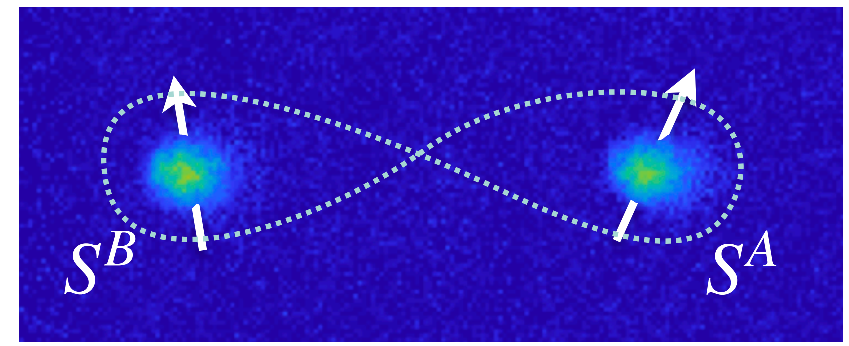
Schmied et al, Science 352, 441 (2016)
Fadel et al, Science 360, 409 (2018)

Perspectives for searches of new physics

Perspectives for searches of new physics

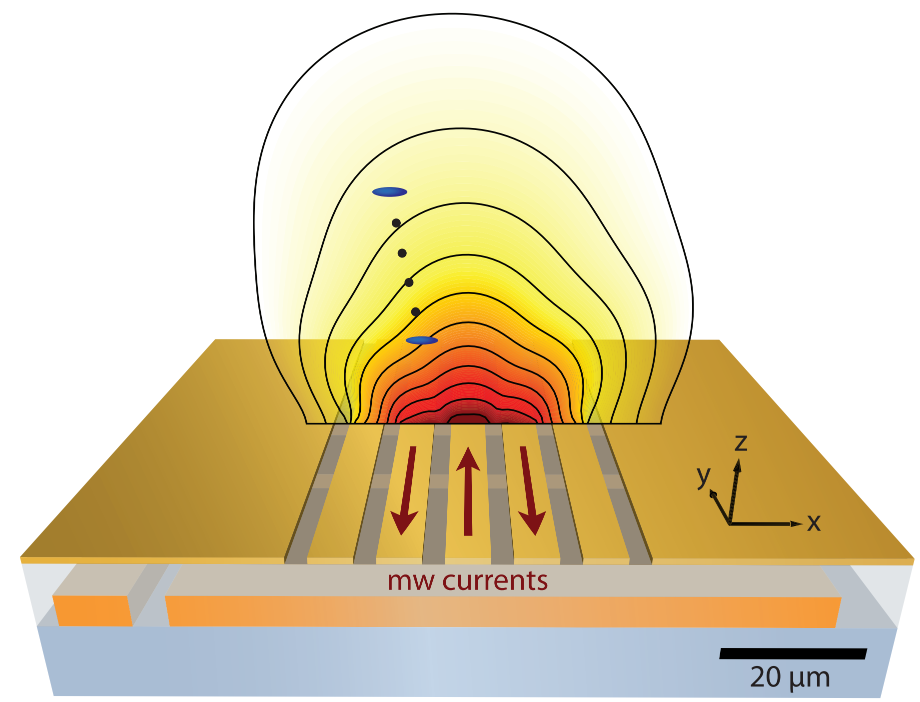
Tests of quantum physics with massive many-particle systems

- strong non-classical correlations (EPR, Bell)
- scaling with particle number N
- decoherence



Quantum metrology close to a chip surface

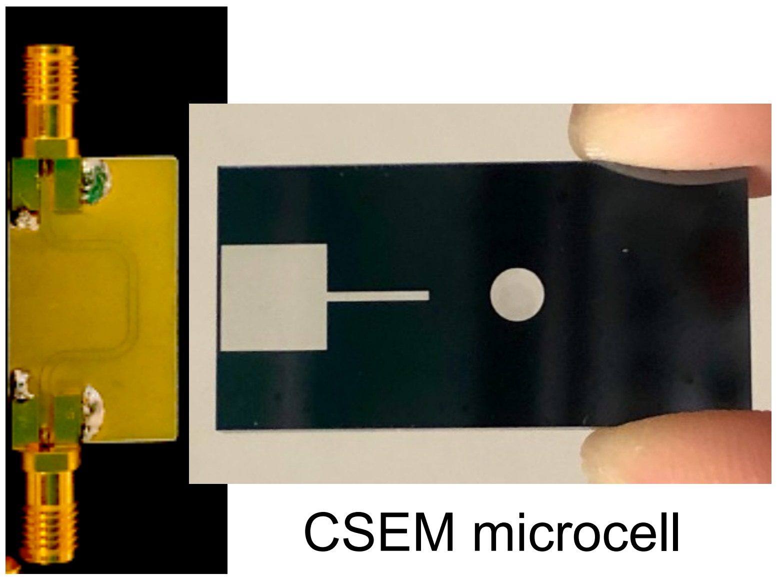
- chip-based atomic clocks and interferometers
- field and force measurements on micrometer scale
- Casimir-Polder forces
- spin-dependent forces
- entanglement-enhanced precision
- measurements with entangled atom arrays



Pezzè et al, Rev Mod Phys 90, 035005 (2018)
Safronova et al, Rev Mod Phys 90, 025008 (2018)

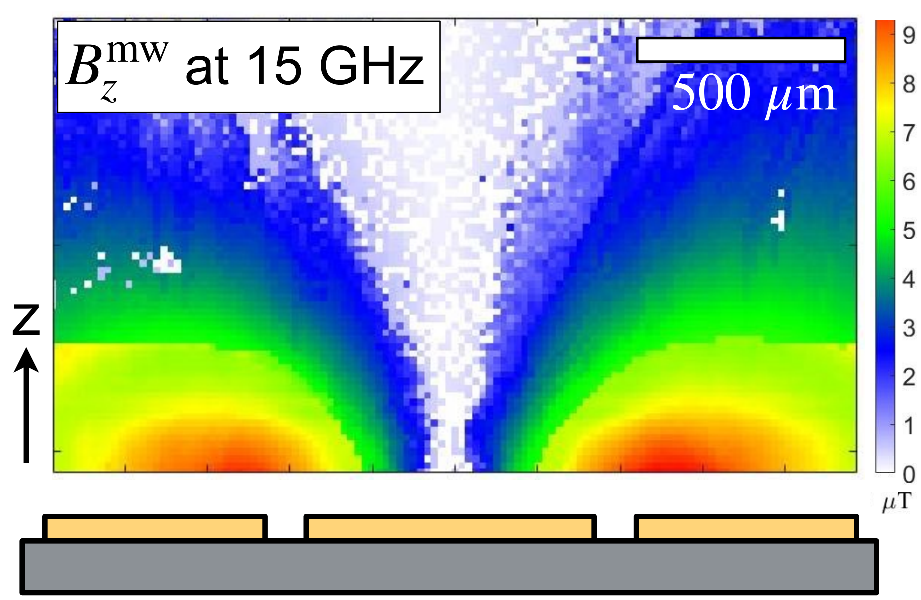
Other quantum metrology activities in our group

Atomic vapor cell sensors



MW circuit

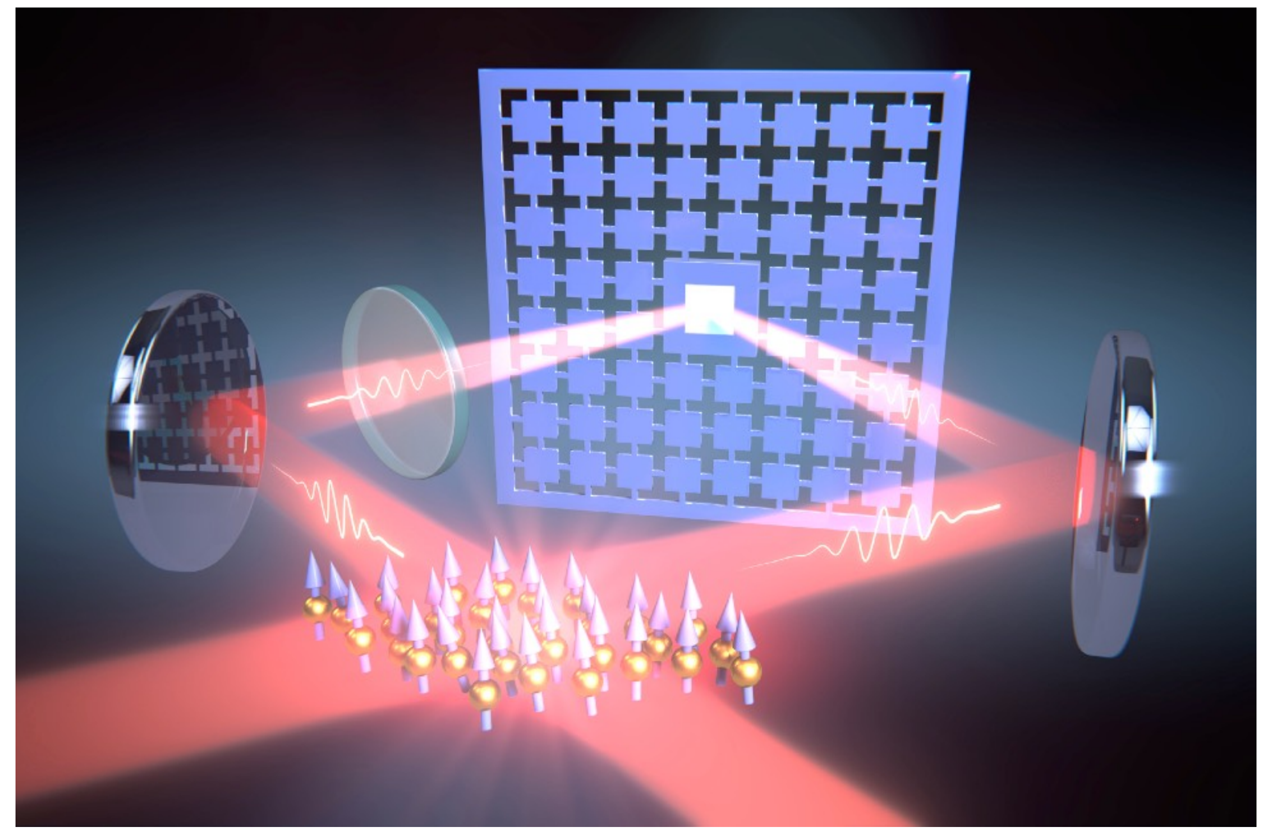
CSEM microcell



Microwave field imaging with Rb atoms

Horsley et al, APL 108, 211102 (2016)
Horsley et al, New J Phys 17, 112002 (2015)

Atom-membrane optomechanics



Strong coupling and coherent control of membrane with atoms

Schmid et al, Phys Rev X (2022)
Karg et al, Science 369, 174 (2020)
Jöckel et al, Nature Nano 10, 55 (2015)

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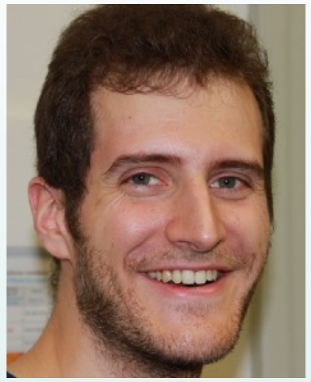
Quantum optics and atomic physics

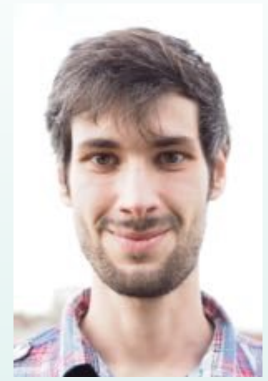
Positions available!


Manel Bosch


Gianni Buser

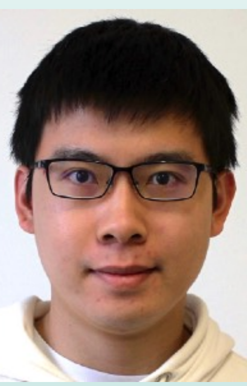

Paolo Colciaghi

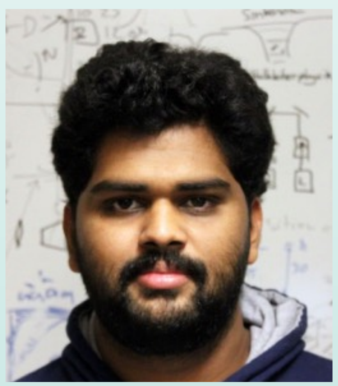

Maryse Ernzer


Matteo Fadel

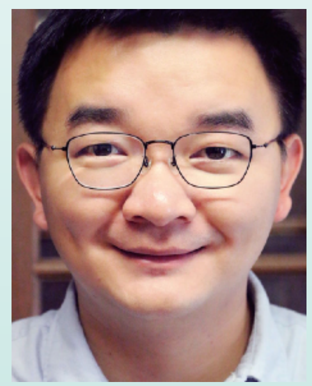

Yifan Li

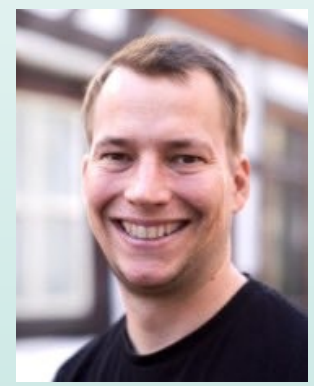

Roberto Mottola

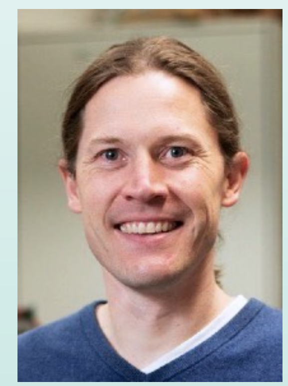

James Ngai


Madhav Saravanan


Gian-Luca Schmid


Yongqi Shi


Tilman Zibold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